

Flow Reactor Studies with Nanosecond Pulsed Discharges at Atmospheric Pressure and Higher

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Fourth Annual Review Meeting of the **AFOSR MURI “Fundamental Mechanisms, Predictive Modeling, and Novel Aerospace Applications of Plasma Assisted Combustion”**

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Objectives (Thrust 2)

- Development and validation of detailed low-temperature plasma fuel oxidation and ignition mechanisms, starting with simple fuels and proceeding to surrogate fuels
- Development of reduced plasma chemical fuel oxidation, ignition, and flameholding mechanisms which can readily be incorporated into predictive multi-dimensional reacting flow codes
- Identification of specific processes critical to the enhancement of basic combustion phenomena by nonequilibrium plasmas, in particular processes involving radical and/or excited metastable species.



Tasks

- **Reaction kinetics studies** with spatially controlled plasma discharges at atmospheric pressure and higher
- **Effect of nanoparticle/catalyst** coupling with plasma enhanced combustion in flow reactors and flames



Approach – Reaction Kinetics

- ***Flow reactor*** experiments between pressures from 0.1 and 3 bar and a temperature range of ambient to 1200 K (quartz chamber).
- Perform ***dilute hydrocarbon oxidation experiments*** in excess nitrogen, argon, or oxygen to minimize the temperature rise of reaction and stretch the reaction spatially over a significant length.
- ***Perturb the reaction at different extents of reaction*** with a spatially defined plasma discharge.
- Measure ***temperature and product species*** by sample extraction and GC/FTIR analysis.
- Perform ***kinetic modeling of the reaction kinetics*** with sensitivity and Green's function analysis, $\partial Y_i(x) / \partial Y_j(x')$.



Progress

Flow Reactor Experiments:

- Experiments on the oxidation of C1-C7 alkanes with and without plasma assisted reaction performed for $T = 300 - 1250$ K and $P = 1$ atm (*to study interactions of plasma and thermal chemistry*).
- Experiments on H₂ oxidation with and without plasma assisted reaction for $T = 300 - 1250$ K and $P = 1$ atm (*to study interactions of plasma and thermal chemistry*).
- *In-situ* OH LIF measurements in progress with and without plasma for H₂ oxidation in collaboration with OSU (Walter Lempert and Igor Adamovich) (*to provide more constraints on model development and link data to other research groups*).
- Plasma assisted kinetics experiments with O₂/N₂/Ar mixtures as a function of temperature were conducted to quantify N_xO_y formation in the presence and absence of fuels (*to determine the levels of NO_x, rates of oxides of nitrogen formation, and potential interaction with hydrocarbon chemistry in flow reactor experiments with N₂*).
- Experiments initiated with nanometer aluminum and carbon particles introduced into flow stream coupled with plasma.

Kinetic Modeling:

- Collaborations were continued with OSU (Igor Adamovich) to model the PSU ethylene oxidation experiments with Hai Wang's mechanism.
- Plasma model coupled to SENKIN and CHEMKIN with formal sensitivity analysis.



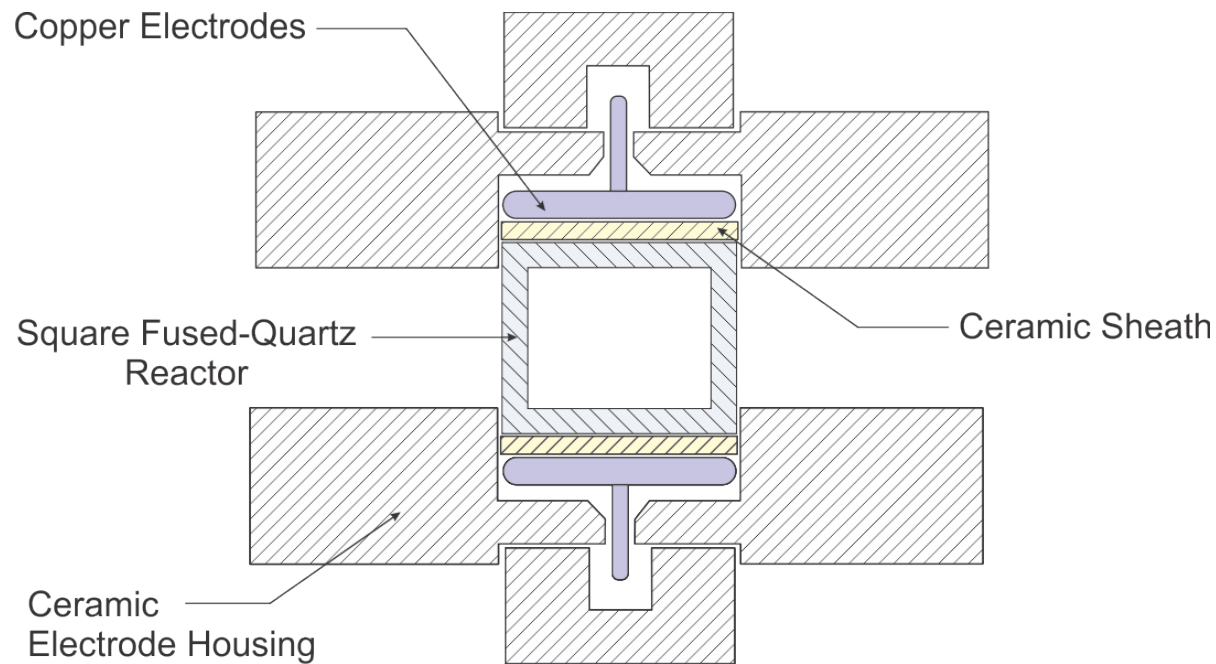
Plasma Flow Reactor



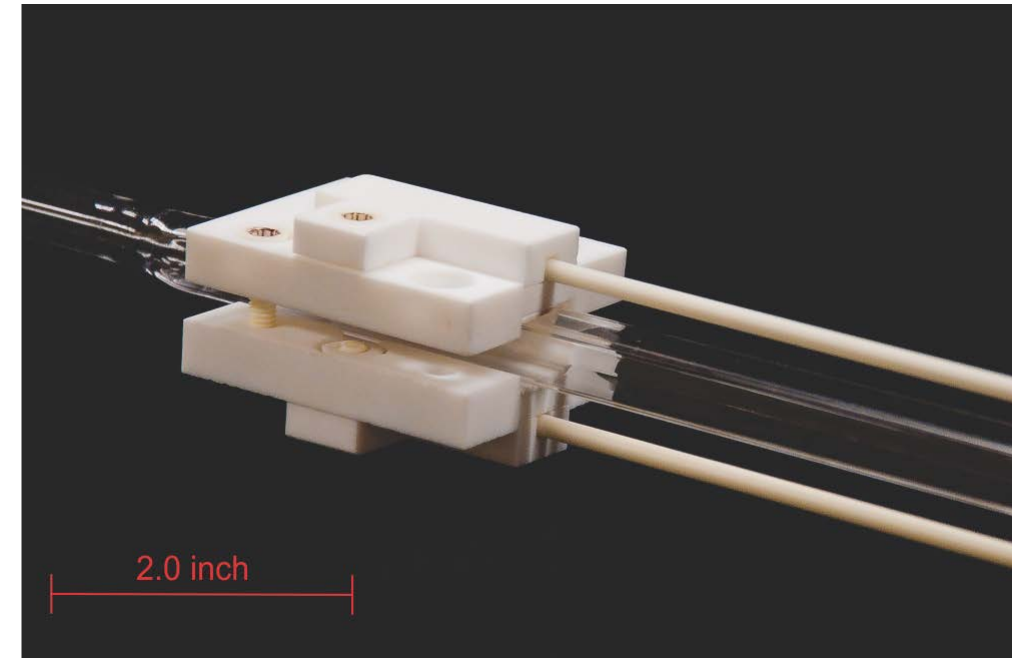
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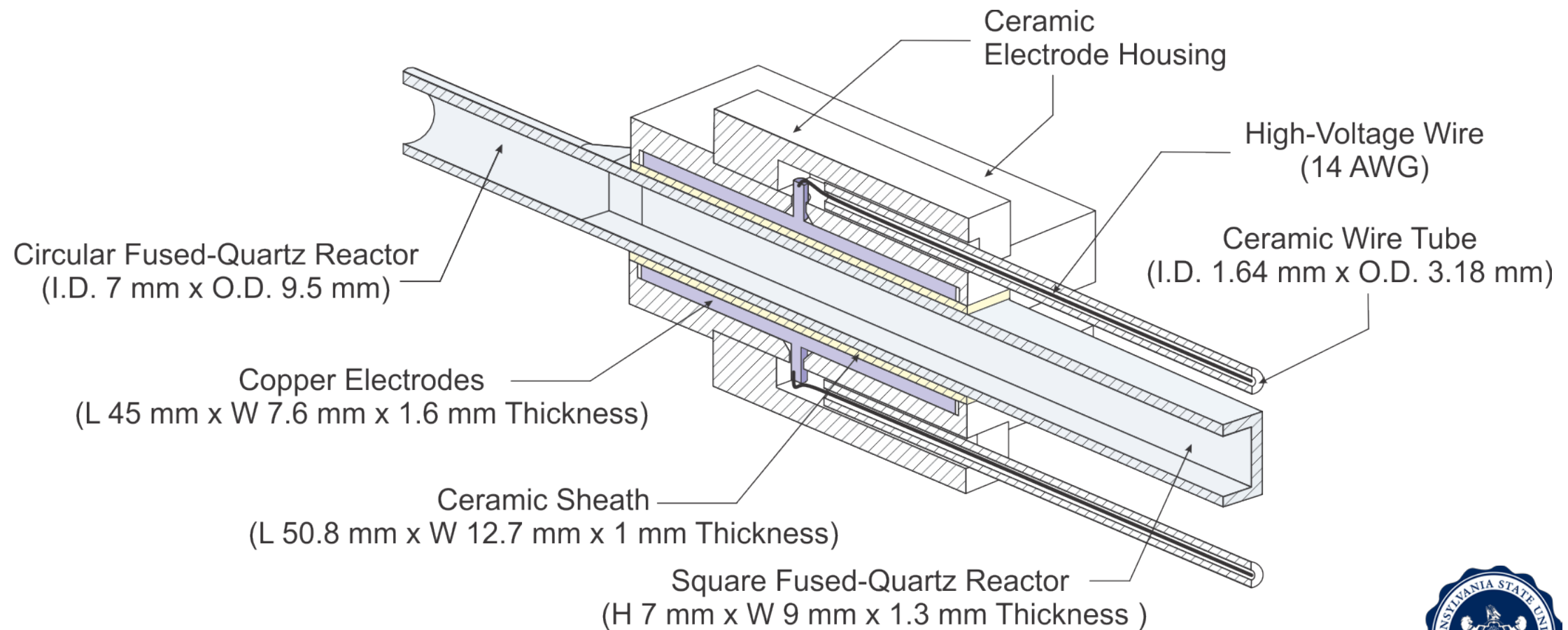
Plasma Discharge Assembly



Cross-Section View (Front)



Actual Image of Assembly

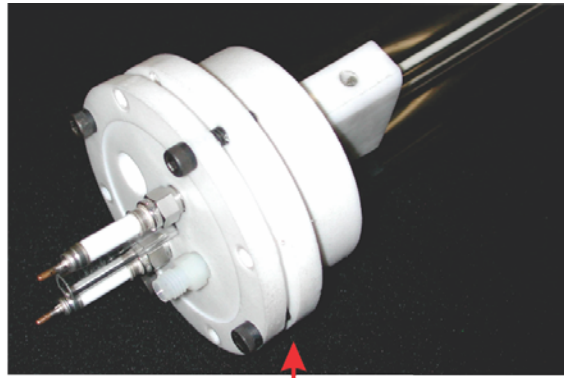


Cross-Section View (Isometric)

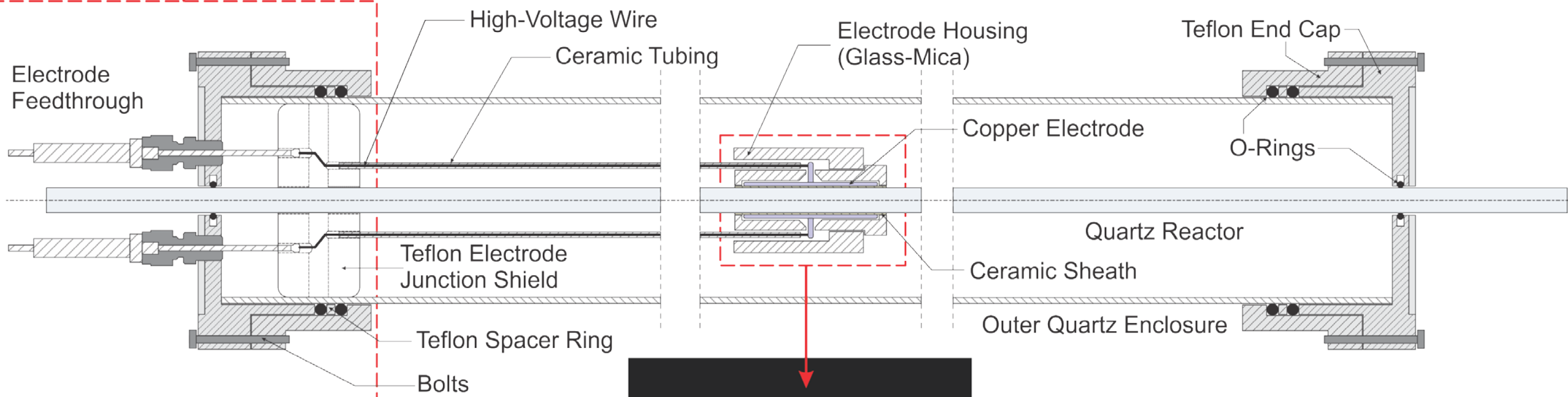


Plasma Flow Reactor Assembly

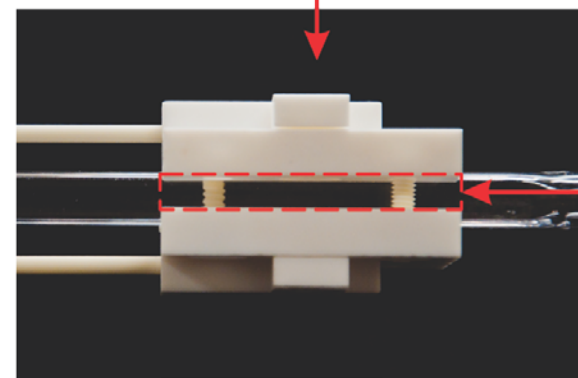
Actual Image Teflon End Caps w/ Electrode Feedthroughs



- The **plasma discharge assembly** is housed in a quartz tube (58mm I.D.) with Teflon end caps
- Actual flow reactor length is 1524 mm (60 in.)



- The **copper electrodes** are connected to ceramic insulated terminal feed-throughs



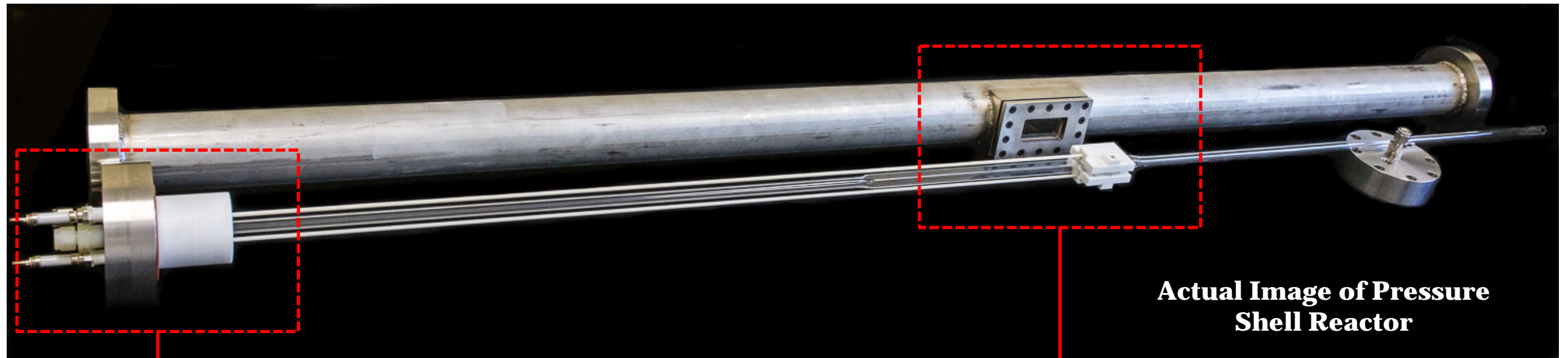
Field of View for
Plasma Imaging

**Actual Image Discharge Assembly
(Side View)**

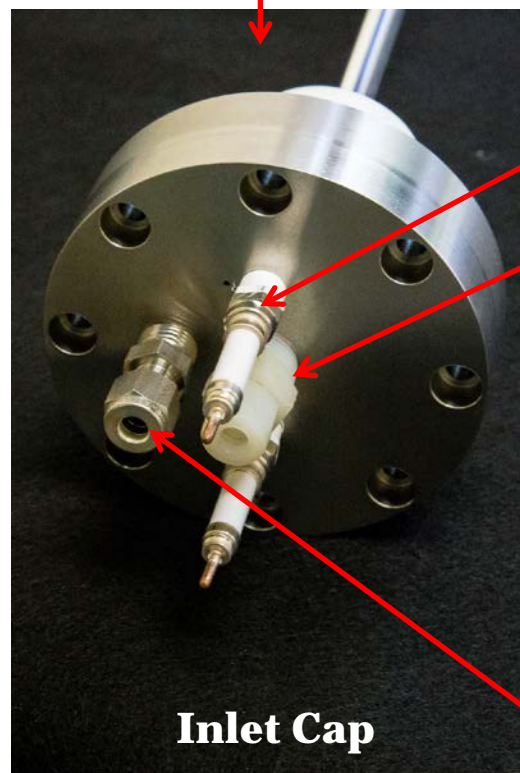


Reactor Assembly for $1 < P < 3$ atm

- Modular plasma discharge reactor can be interchanged with redesigned pressure shell to perform kinetic studies at $P > 1$ atm



Actual Image of Pressure Shell Reactor

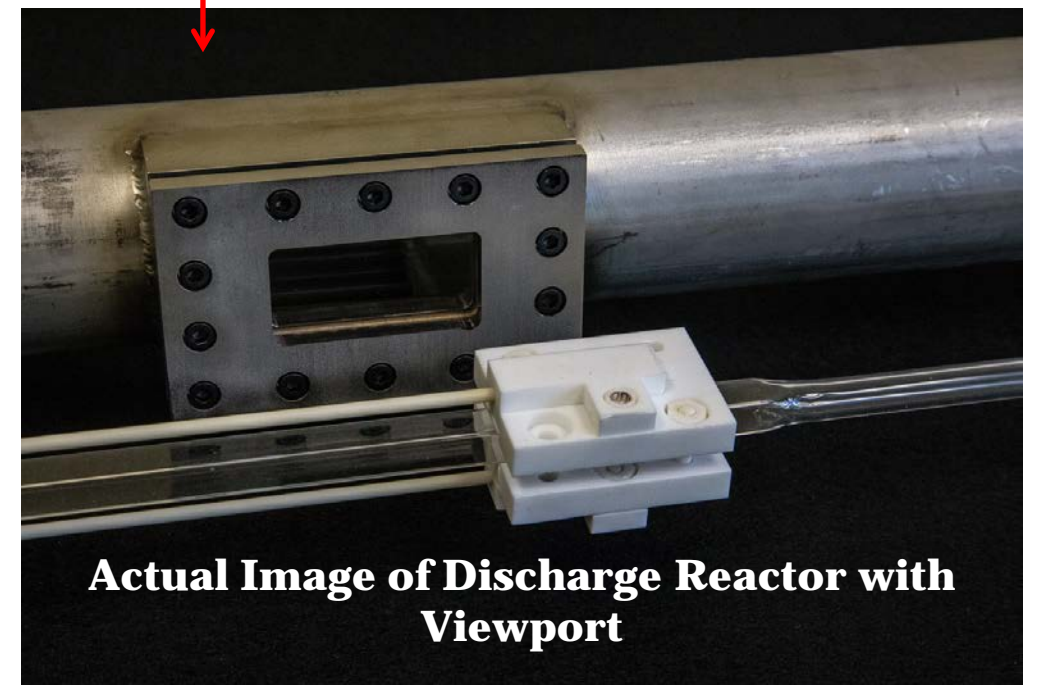


Electrode Feedthroughs

Gas Mixture Inlet

Inlet Cap

Pressure Purge Gas Inlet



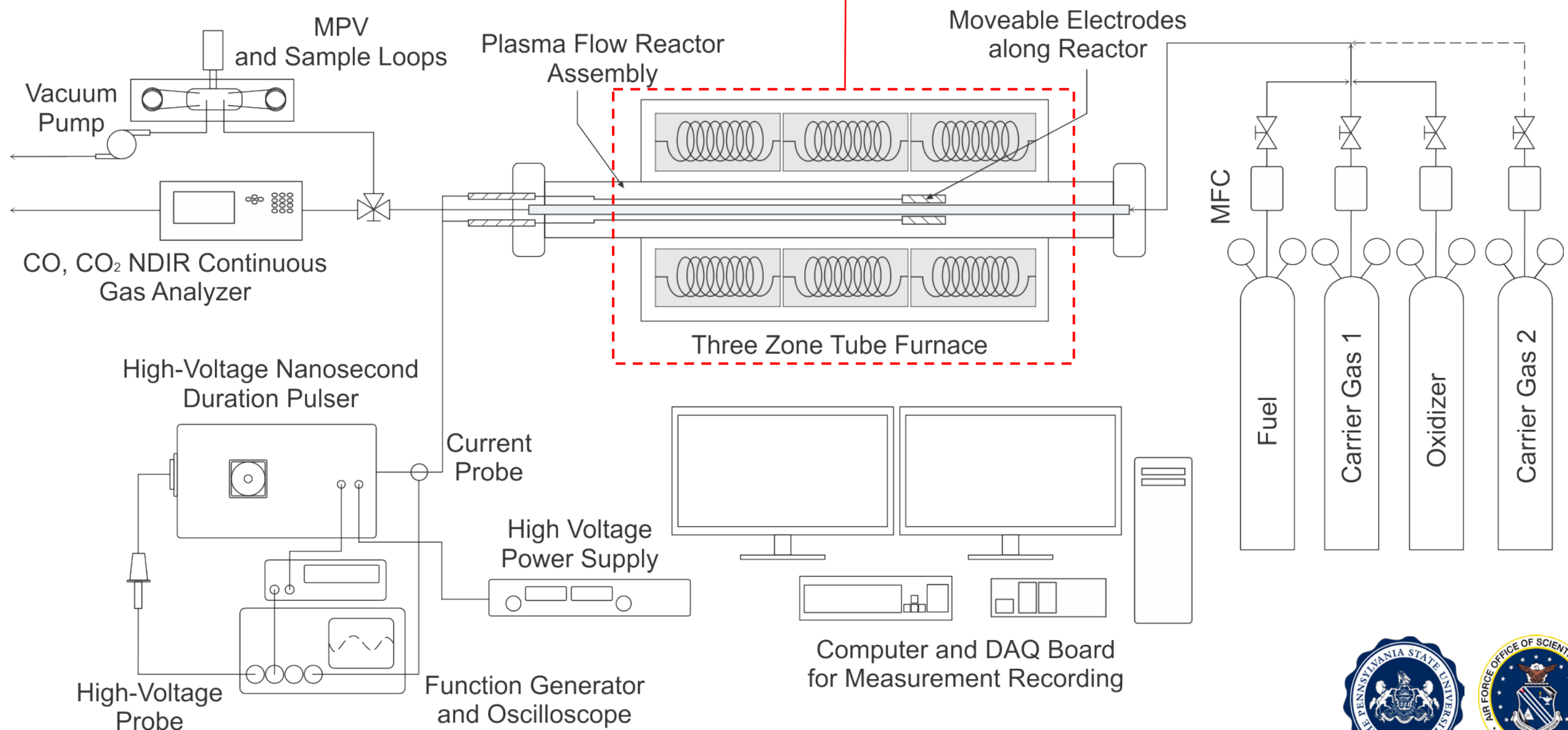
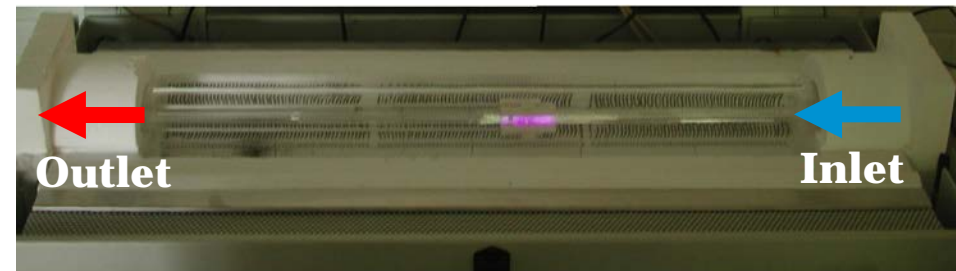
Actual Image of Discharge Reactor with Viewport



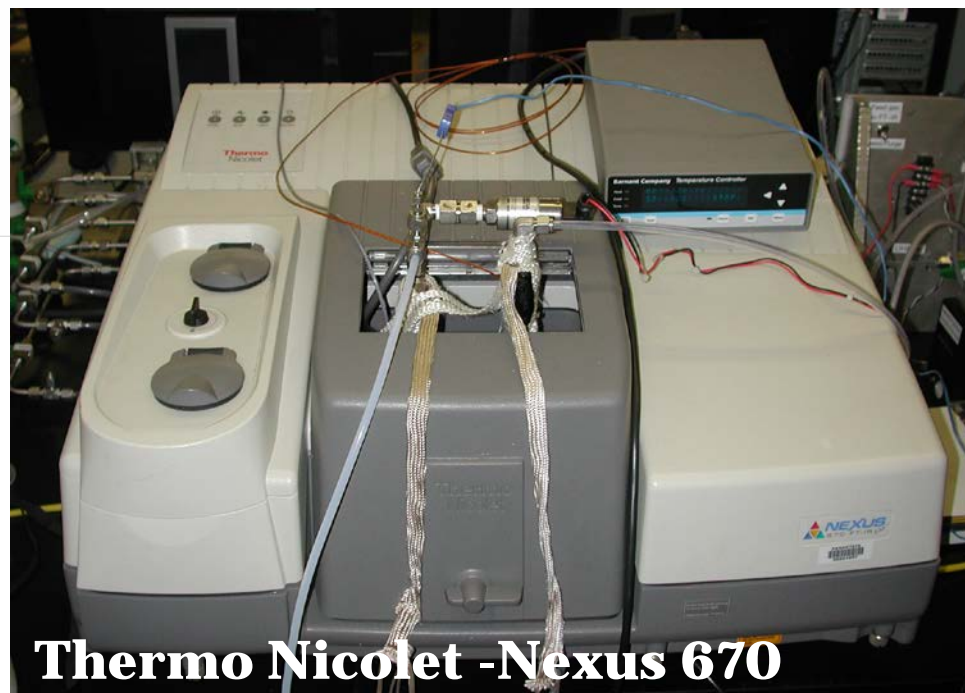
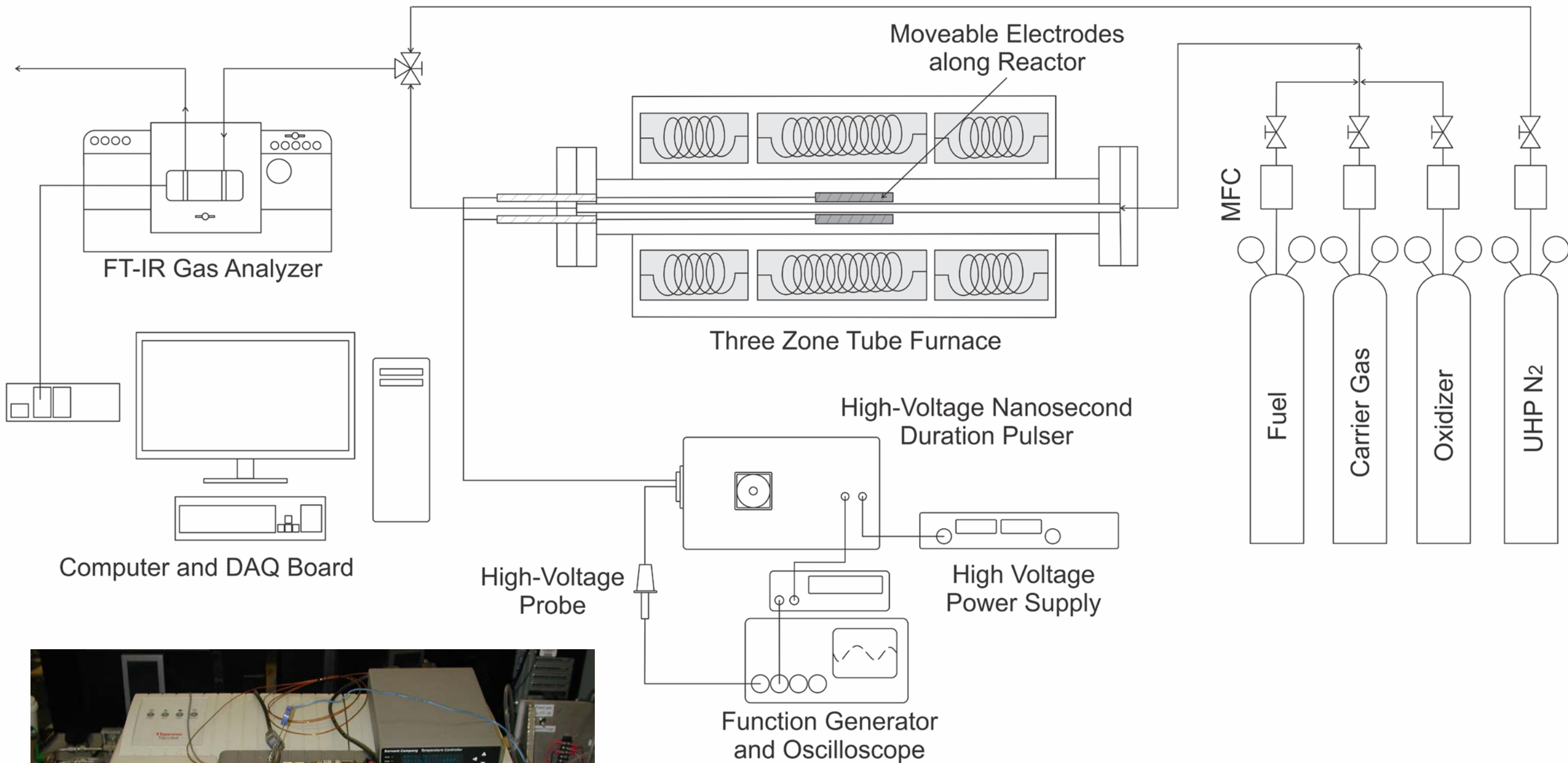
Plasma Flow Reactor Experimental Facility

- Heating is achieved using a **three-zone tube furnace** with a length 609 mm (24 in.)
- Product species analysis performed using **NDIR** (online) and **Gas Chromatography** (offline)

**Actual Image Tube Furnace w/
Plasma Flow Reactor**



Experimental Facility – cont'd

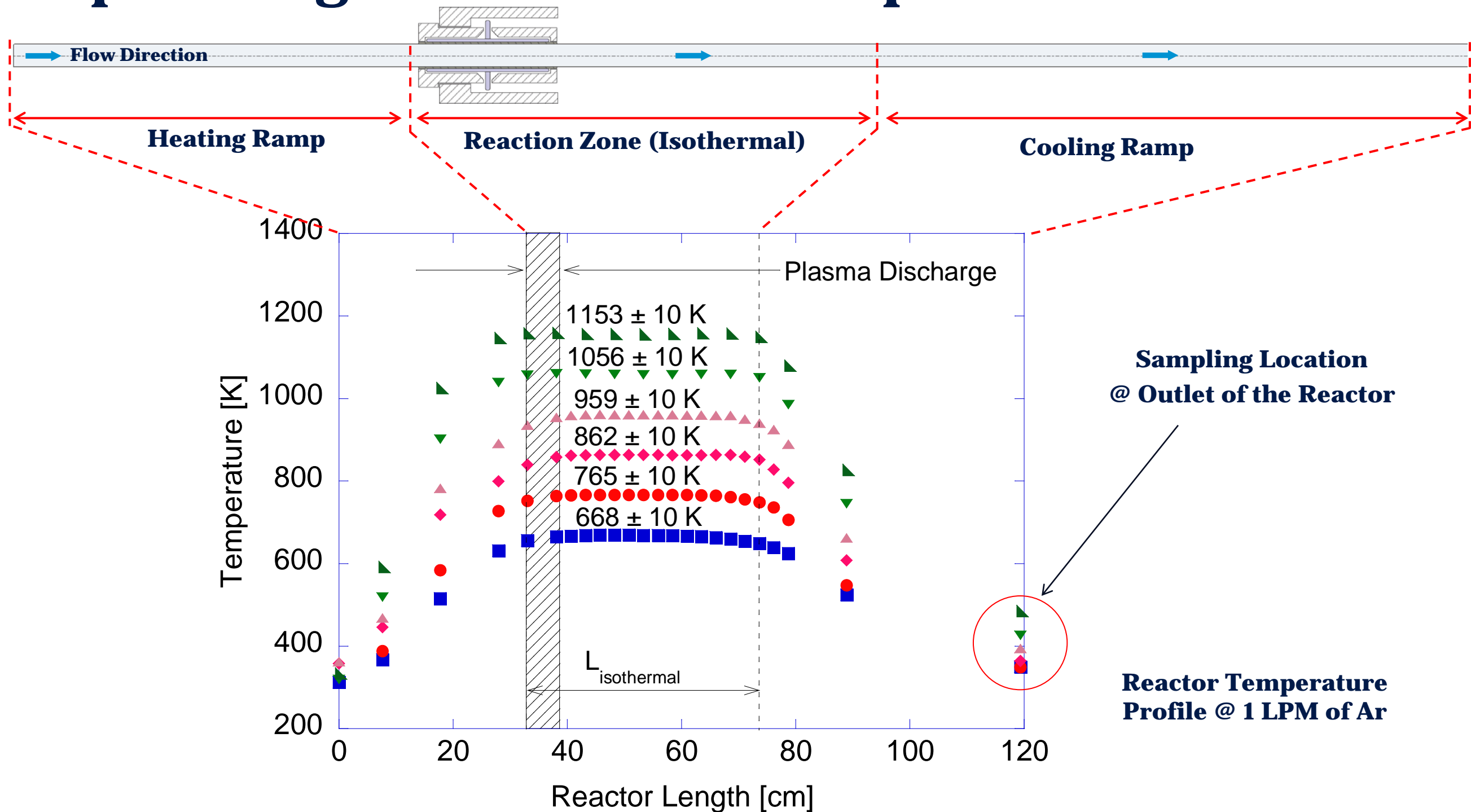


Thermo Nicolet -Nexus 670

- **FTIR** (online) connected to exhaust stream of reactor
- Capable of detecting hydrocarbon and nitrogen-containing species (i.e. NO, NO₂, N₂O)



Operating Conditions - Temperature



- The measured temperature profiles are used to establish an empirical correlation with the tube furnace temperature over a range of $350 \text{ K} < T_{\text{iso}} < 1250 \text{ K}$. The correlation is used for kinetic modeling
- Experiments verify that heating from the plasma discharge is negligible in the diluent flow
- In Ar/O₂ flow, $\sim 10 \text{ K}$ increase in gas temperature observed at the maximum voltage setting for a given reactor temperature of 814K



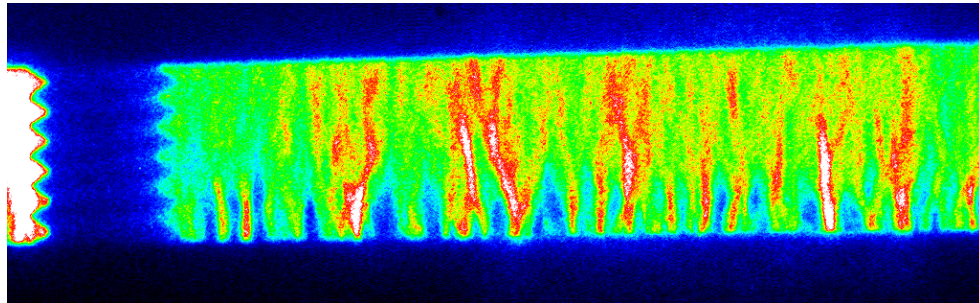
Operating Conditions - Plasma Discharge

Experimental Conditions: $P = 1 \text{ atm}$, $Q = 1 \text{ LPM Ar}$, $\text{Gate} = 10 \text{ } \mu\text{sec}$

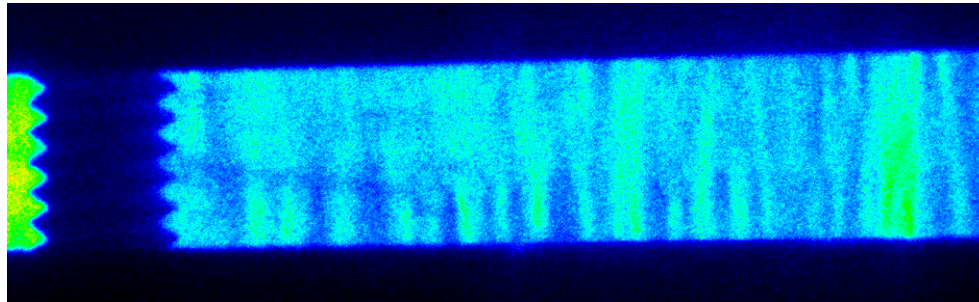
Plasma Discharge : $V_{\text{plasma}} = 15 \text{ kV}$, $\nu = 1 \text{ kHz}$

ICCD Single Pulse Images

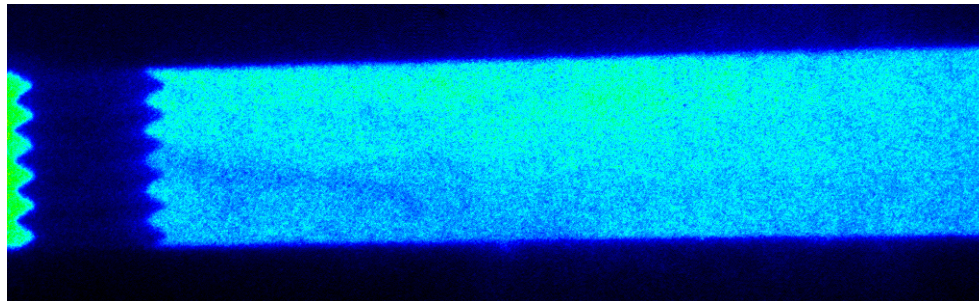
298 K



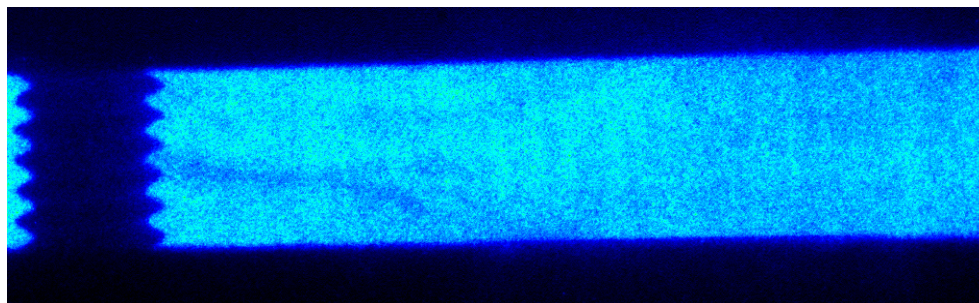
427 K



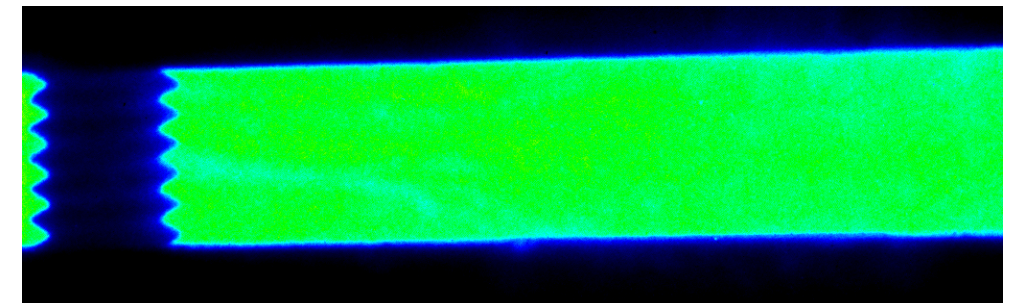
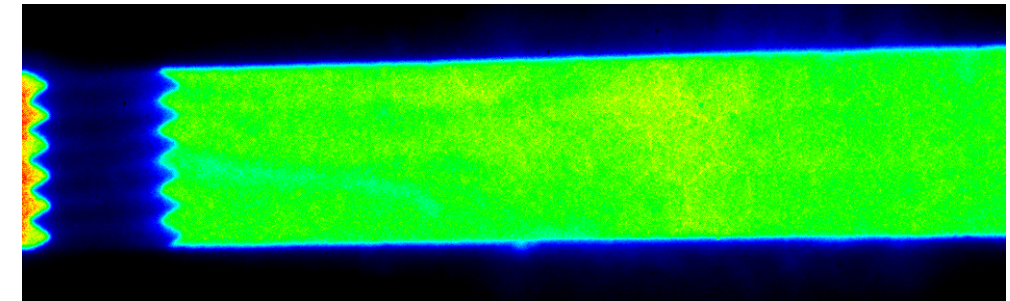
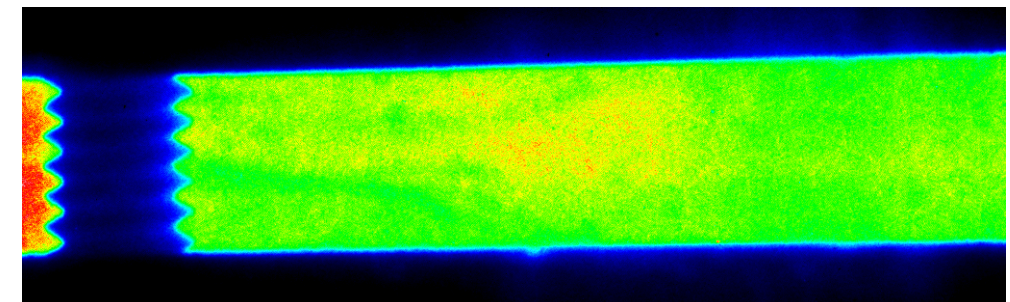
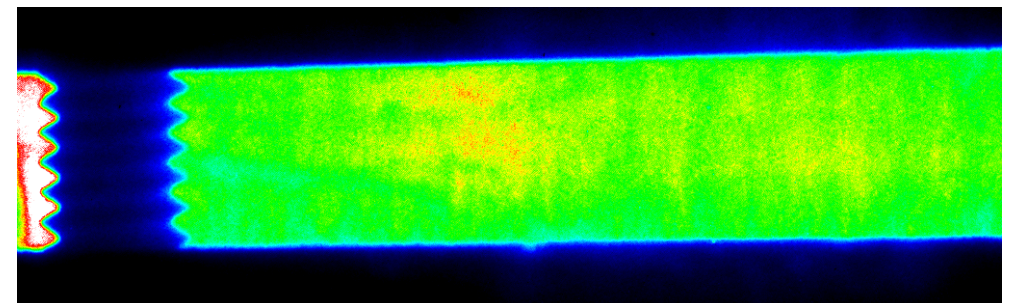
620 K



814 K



ICCD Multiple Images (average of 50)



Brief Review of Previous Results



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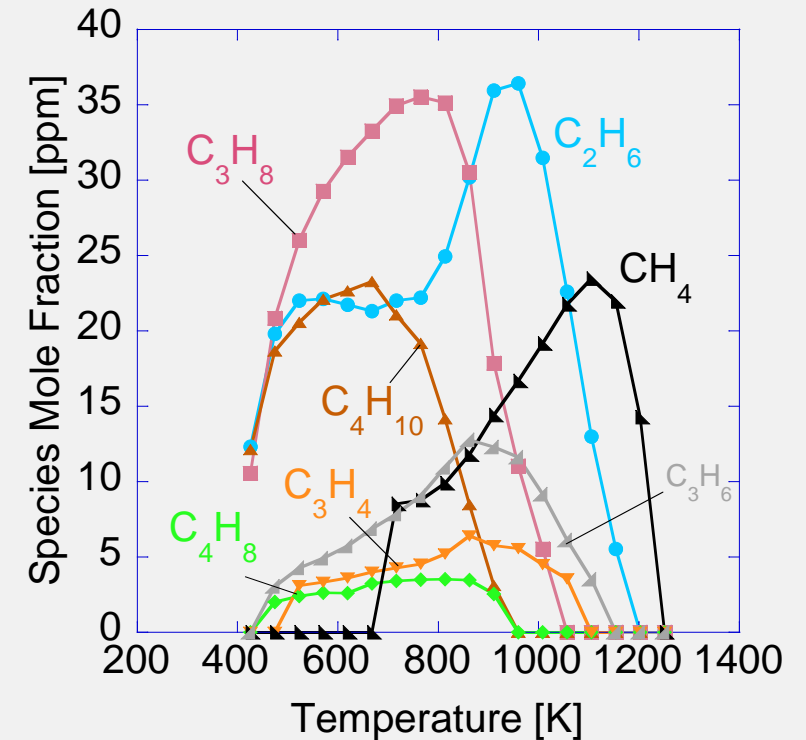
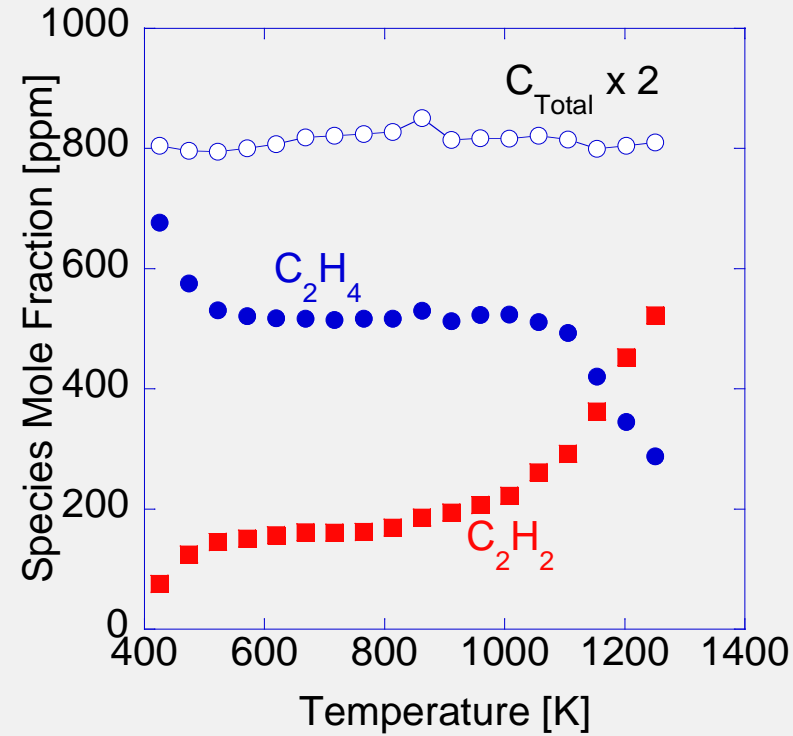
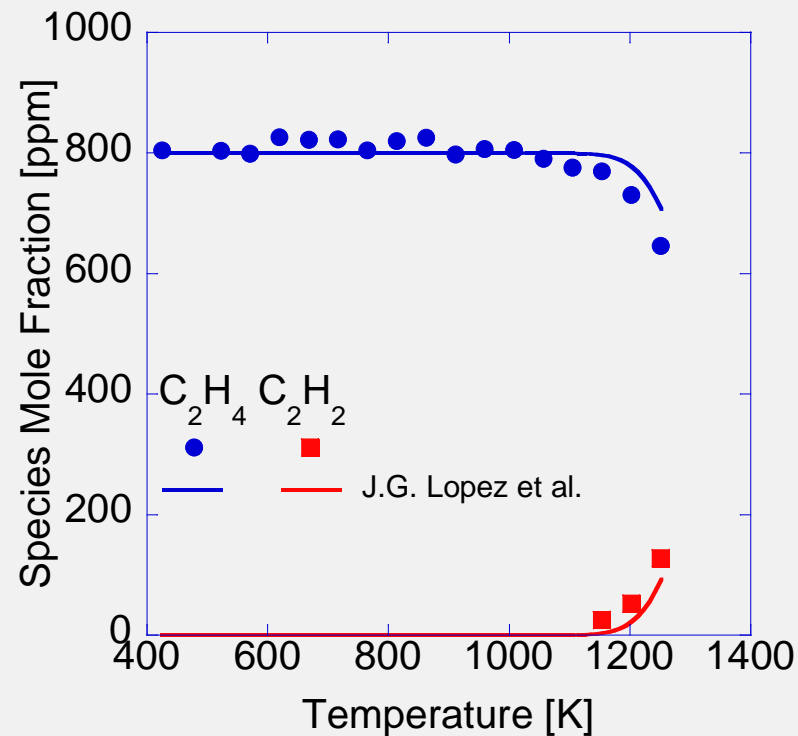
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C₂H₄ Pyrolysis and Oxidation Experiments

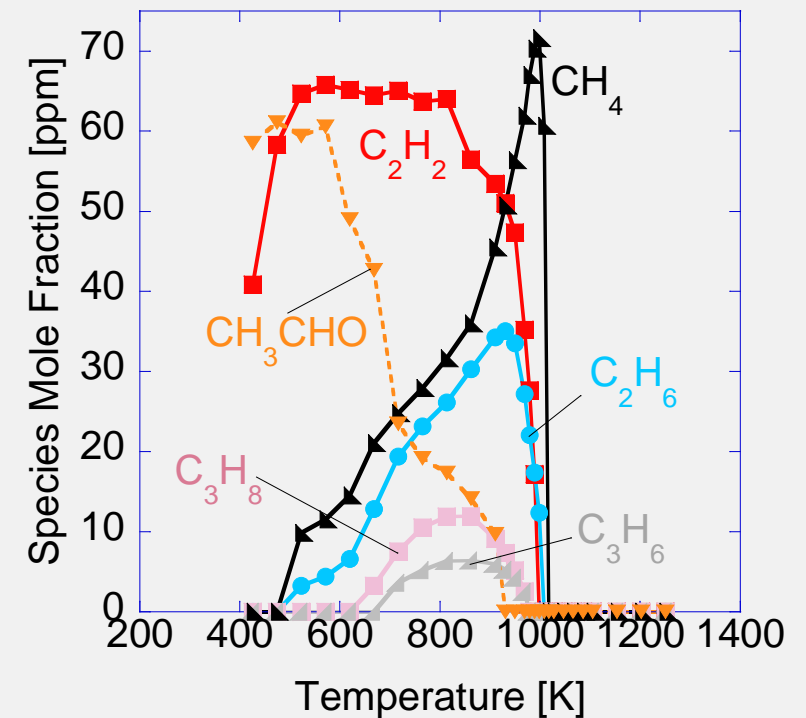
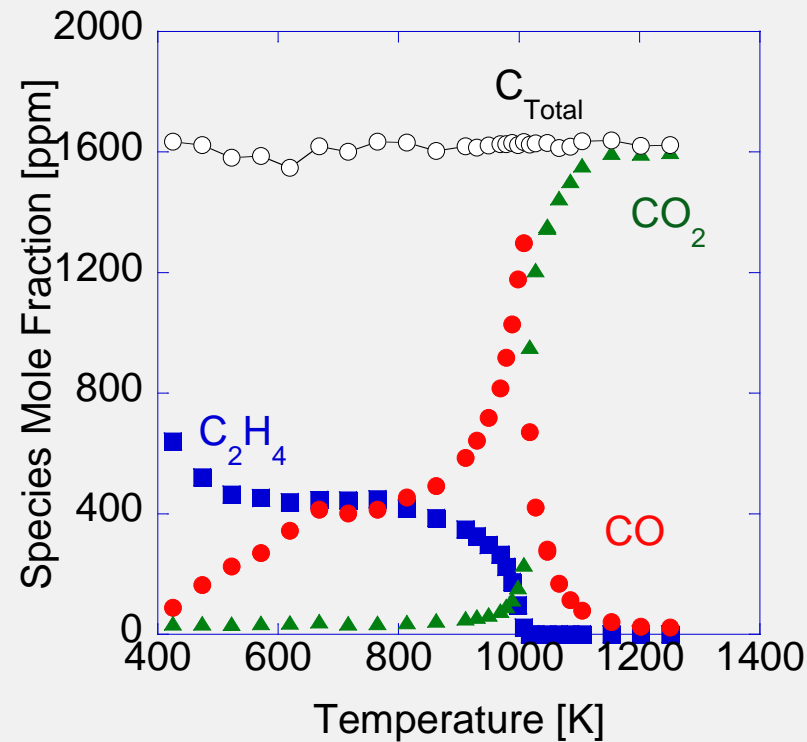
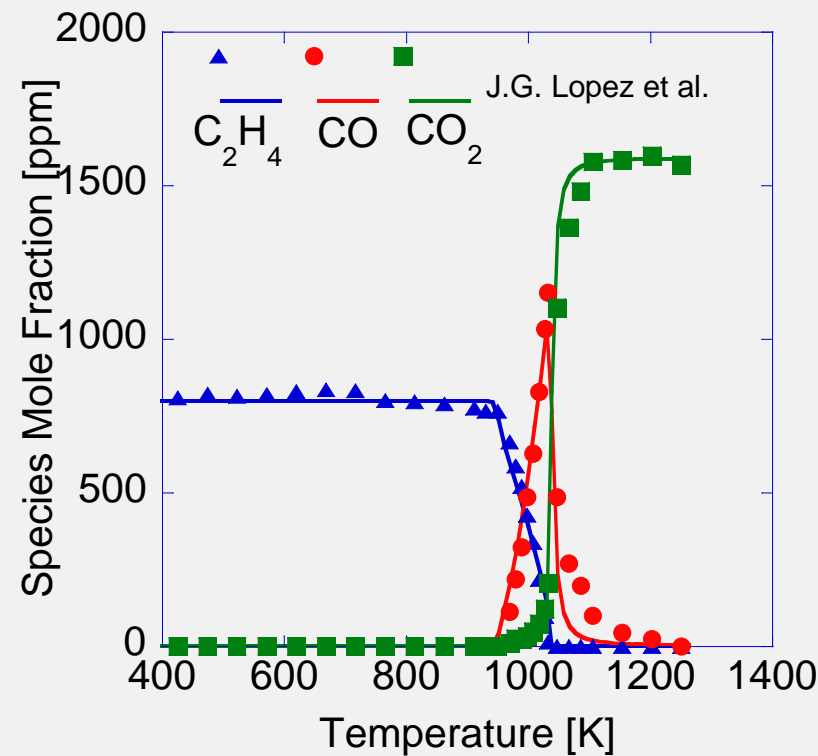
Thermal

Plasma Assisted

Pyrolysis



Oxidation



Experimental Conditions: P = 1 atm, Q = 1 LPM, 800ppm C₂H₄/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz

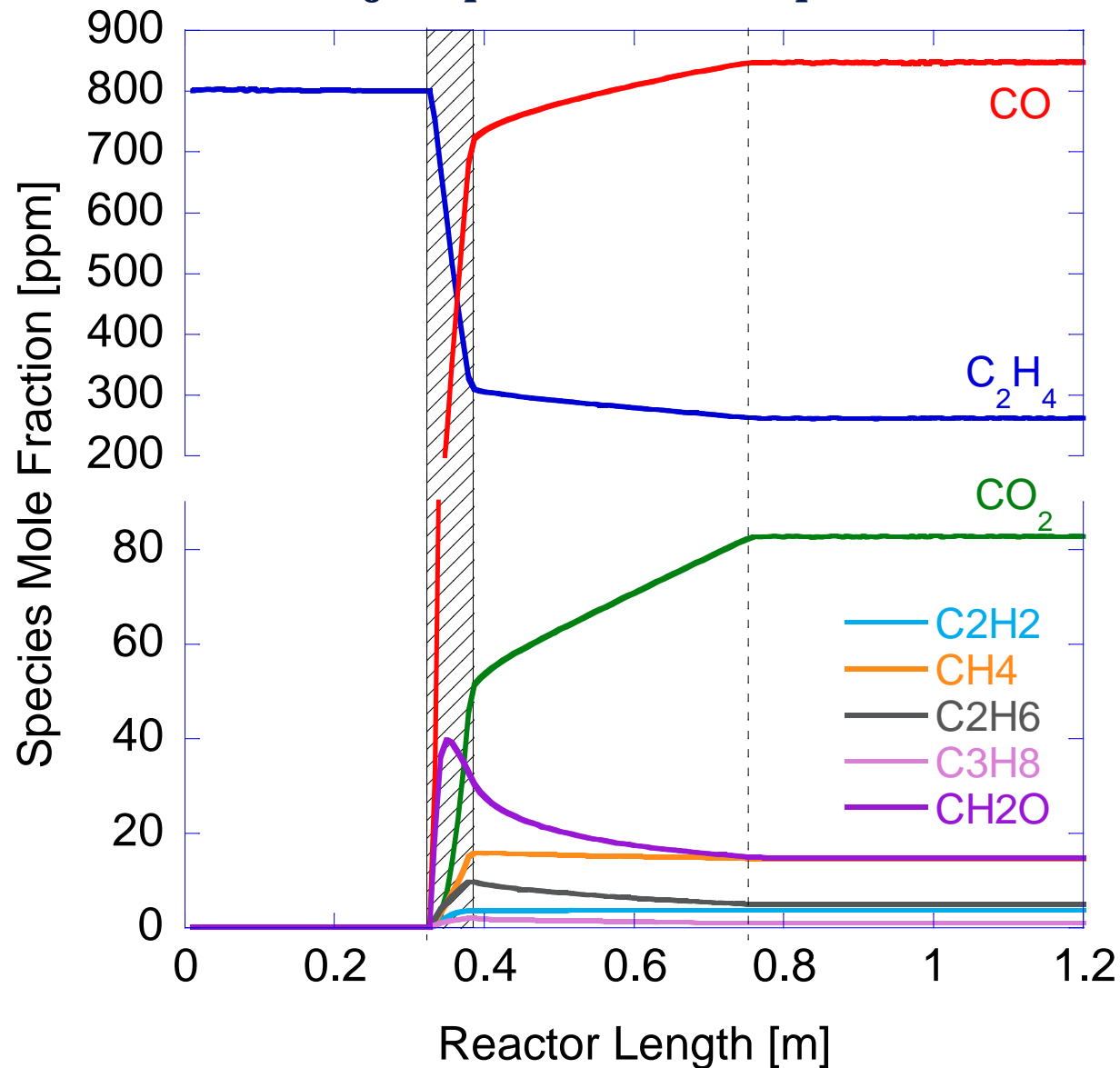


Modeling Results for a Single Experiment

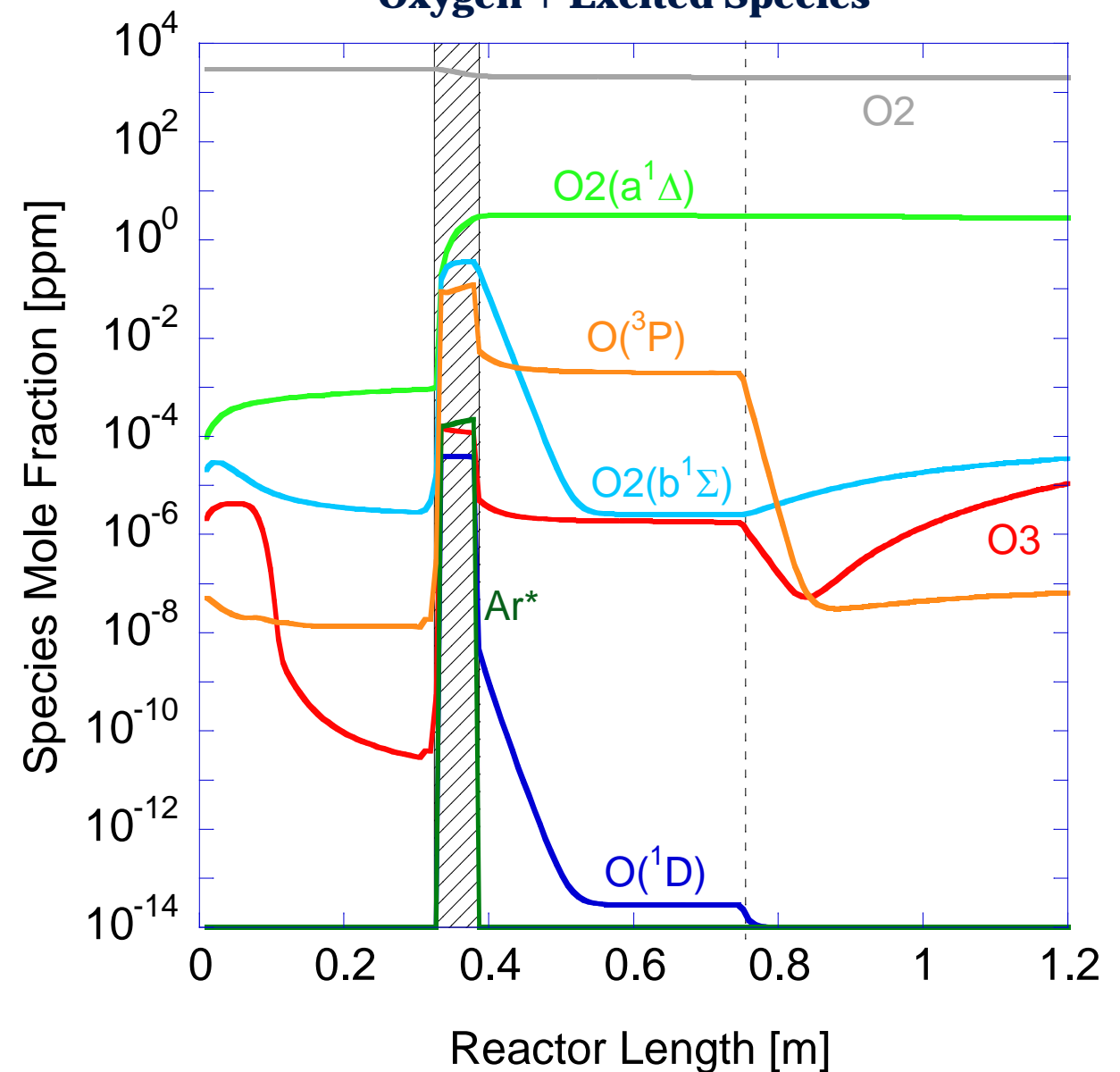
Modeling Conditions: $P = 1$ atm, $Q = 1$ LPM, $T = 863$ K, 800ppm C_2H_4 / 3000ppm O_2 / Balance Ar

Plasma Conditions: 0.043 meV/molecule/pulse

Major Species + Minor Species



Oxygen + Excited Species



- Most of the reaction is isolated in the plasma region, with some further reaction occurring in the isothermal region
- Experimental results correspond to species concentration at the exit of the reactor



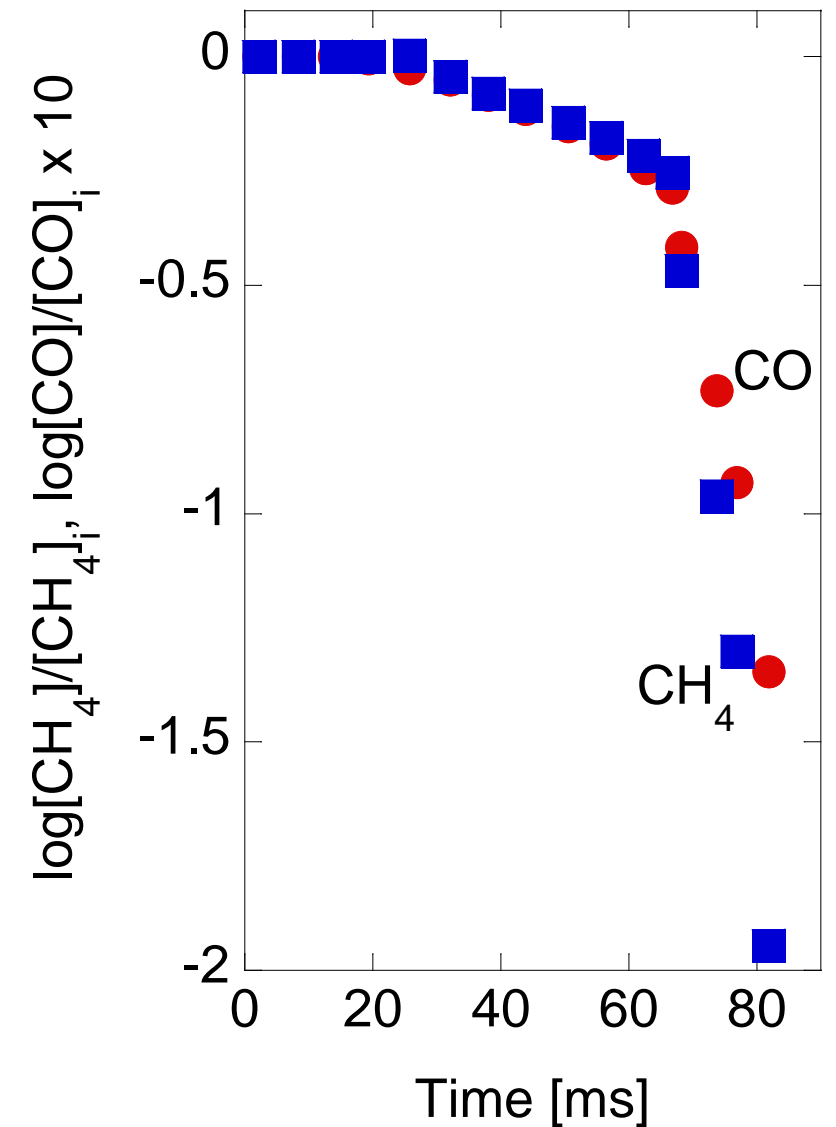
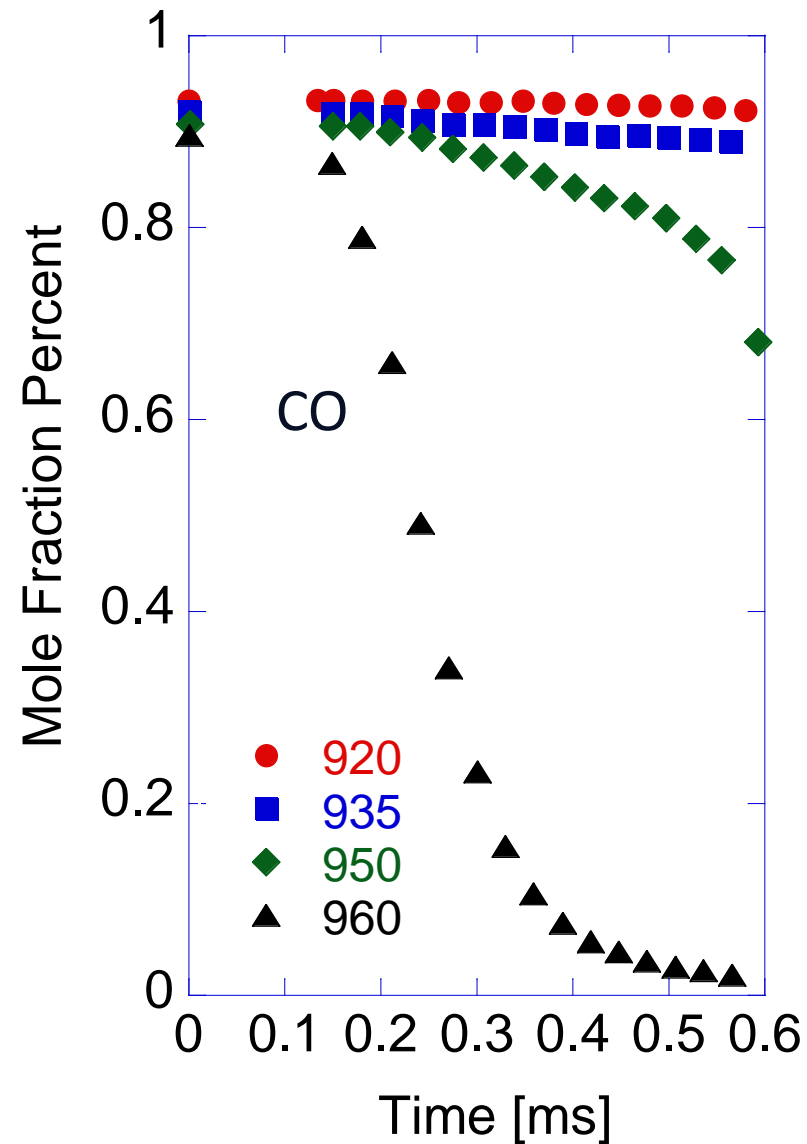
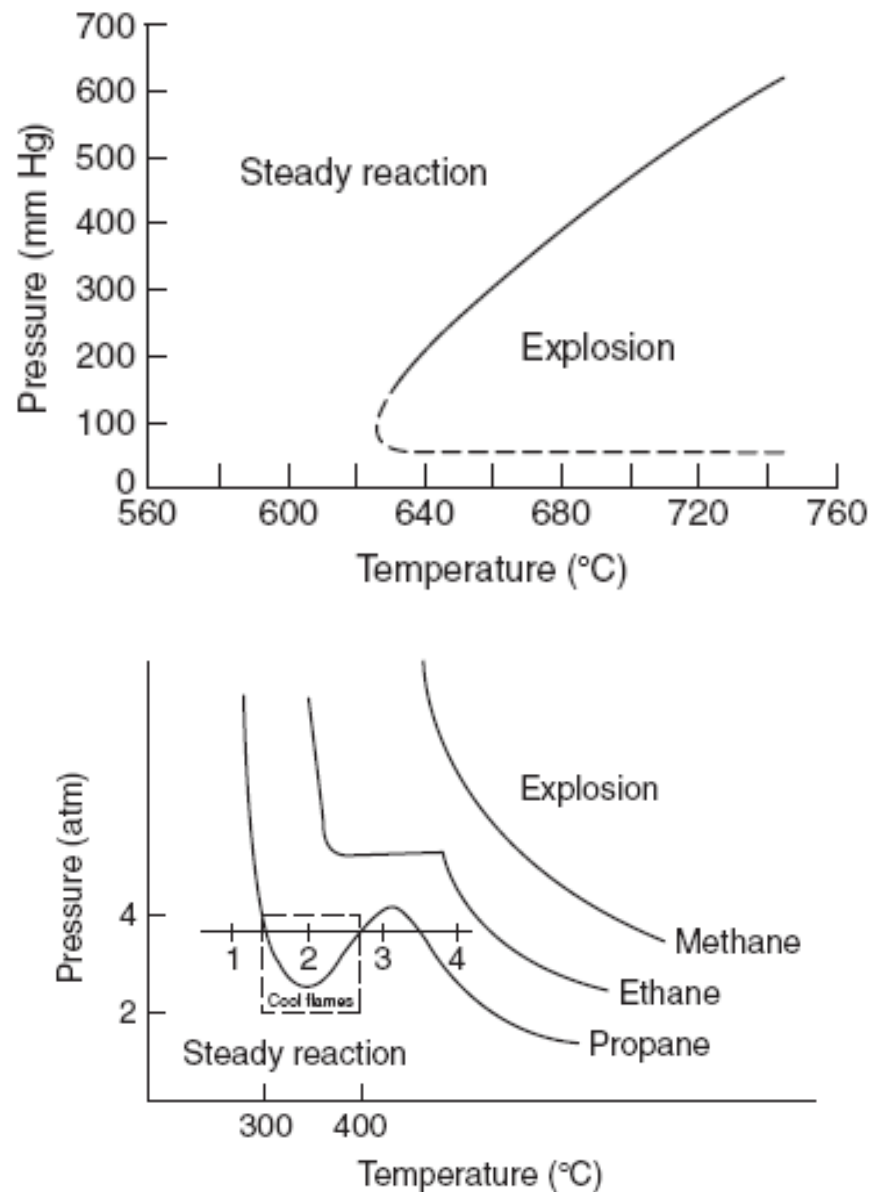
C₁-C₇ Alkanes Plasma Assisted Oxidation



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Thermal Explosion Limits



I. Glassman and R.A. Yetter, **Combustion**, 4th Ed, Academic Press, 2008

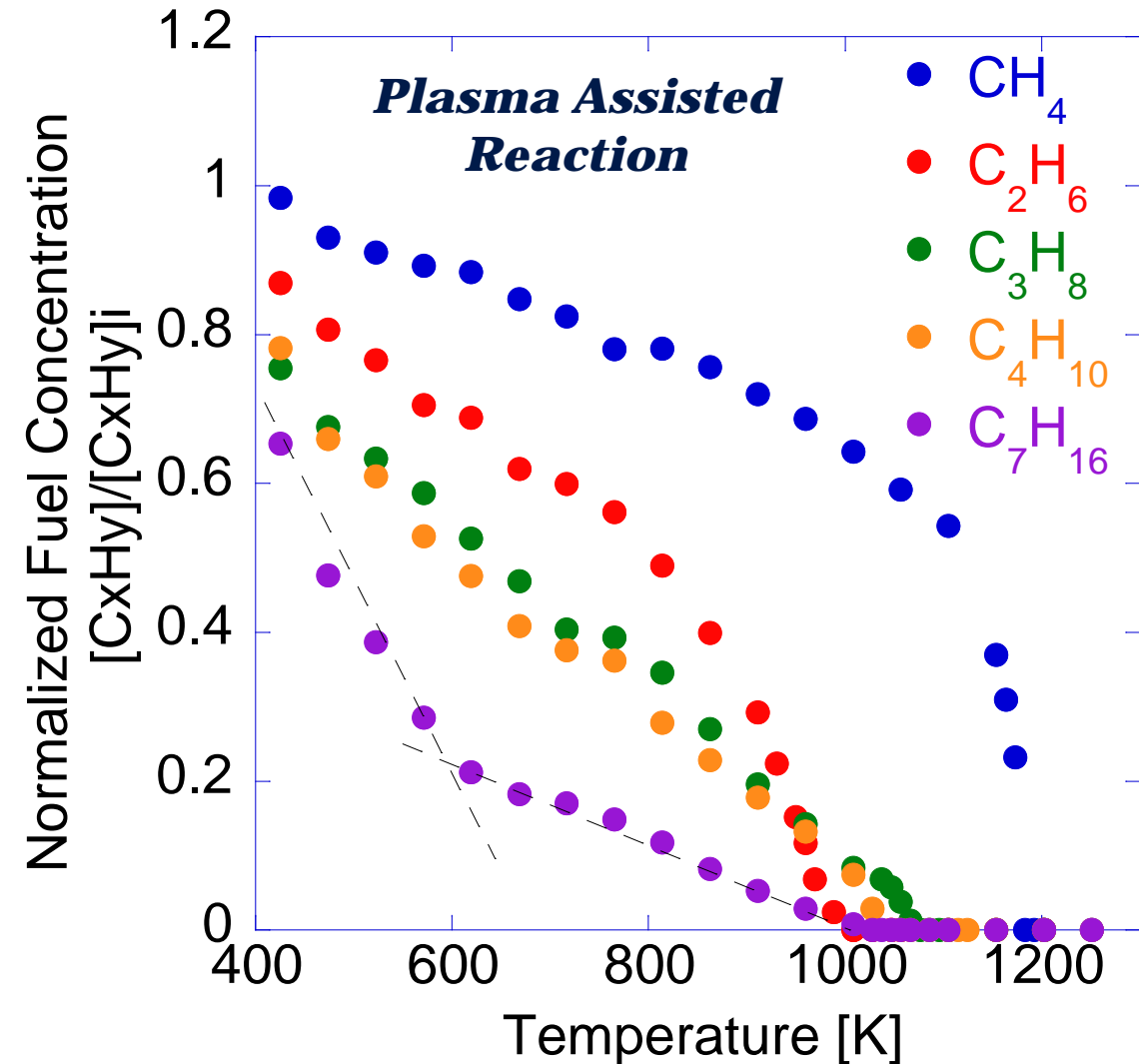
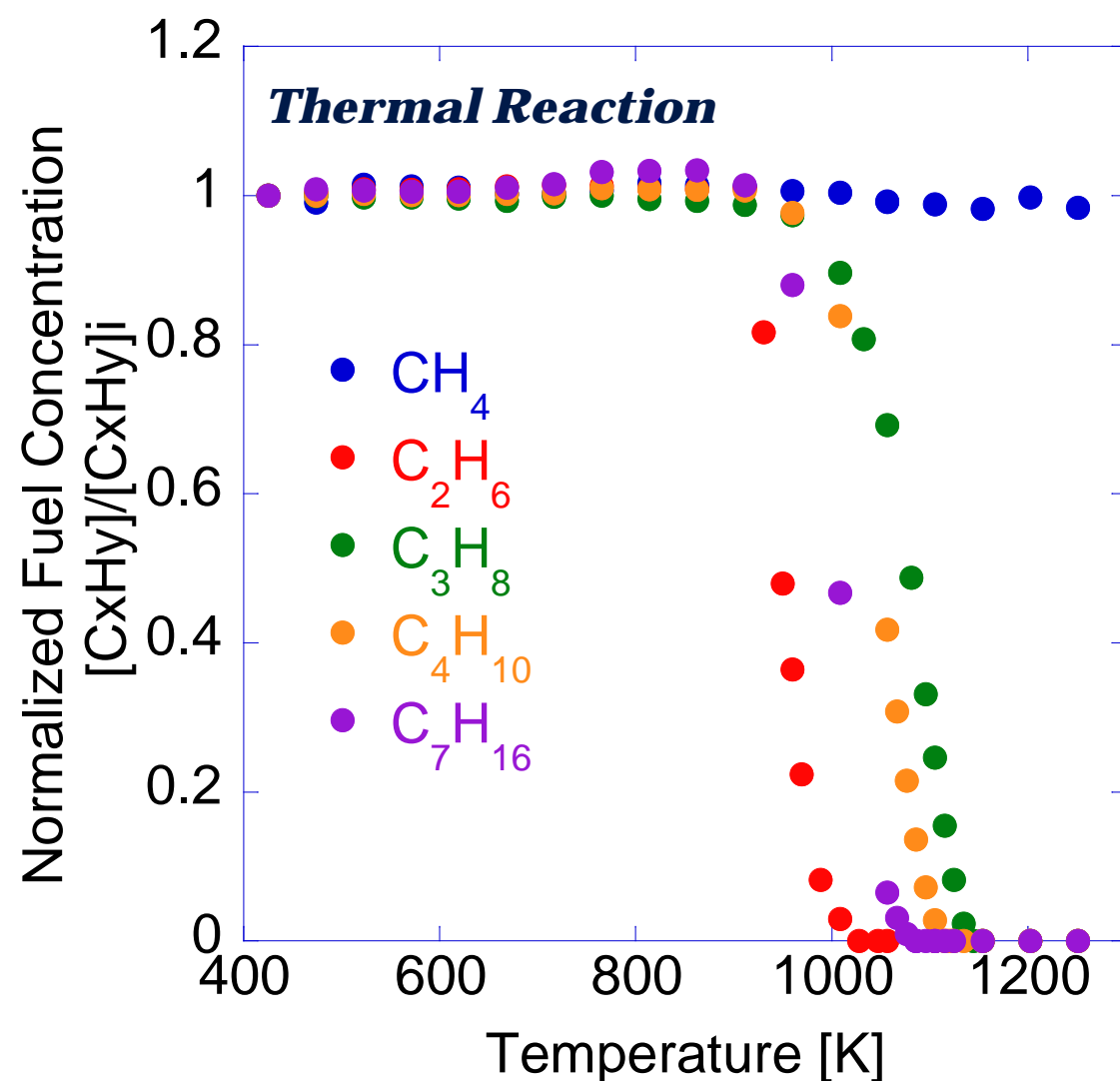
Yetter, R.A. and Dryer, F.L., **Proceedings of the Combustion Institute**, 24, 757, 1992.



C₁-C₇ Alkane Fuel Consumption

Experimental Conditions: P = 1 atm, Q = 1 LPM, 1600ppm C_xH_y/3000ppm O₂ / Ar balance

Plasma Conditions: 10 kV, ν = 1 kHz



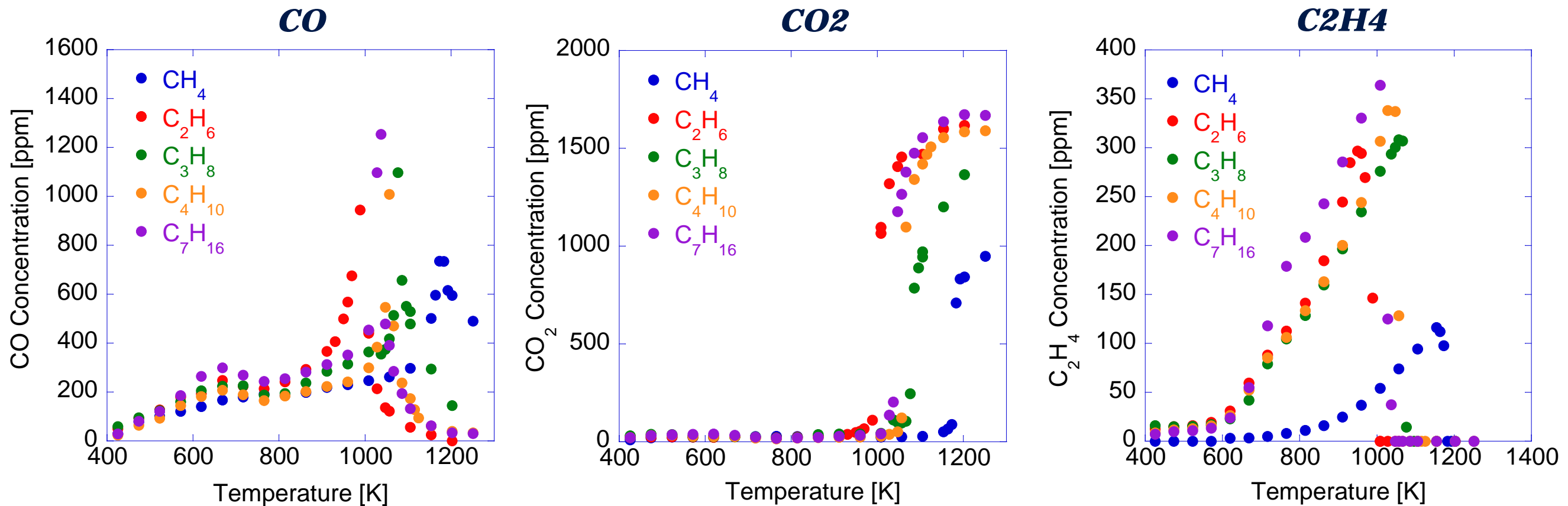
- Without the plasma, onset of fuel consumption occurs for T > 900 K. With the plasma, onset of fuel consumption occurs at T = 420 K for all the fuels.
- The plasma also lowers the temperature for complete consumption of all fuels (the temperature for onset of high temperature ignition).
- For C₃ and larger fuels, a transition in reaction rate is observed 600 and 700 K.



Major Intermediate Species Generation

Experimental Conditions: $P = 1$ atm, $Q = 1$ LPM, 1600ppm C_xH_y /3000ppm O_2 / Ar balance

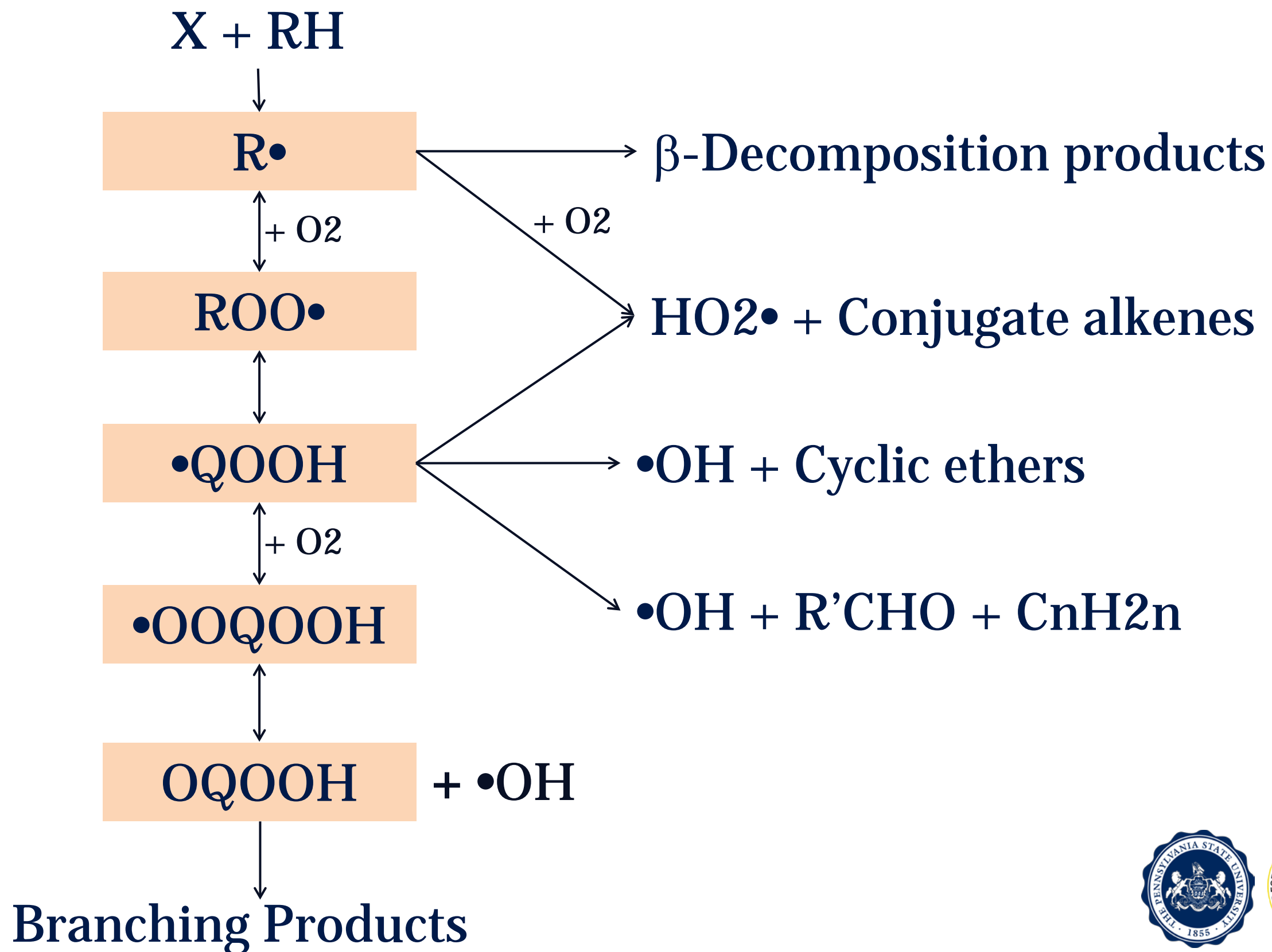
Plasma Conditions: 10 kV, $\nu = 1$ kHz



- Before the onset of thermal effects, the plasma has a consistent effect on the formation CO; once the thermal effect is initiated both the plasma and thermal reactions contribute to forming and consuming CO
- Below 960K, very little heat producing CO_2 is formed.
- With the exception of CH_4 , all fuels appear to form similar amounts of C_2H_4 from 420K until the temperature where C_2H_4 consumption exceeds its formation.

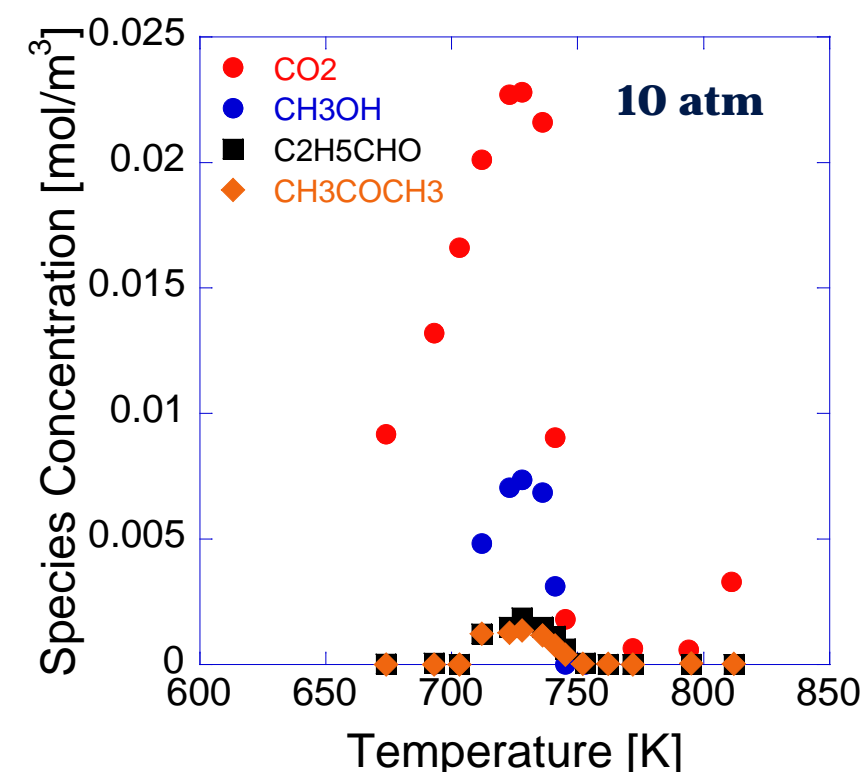
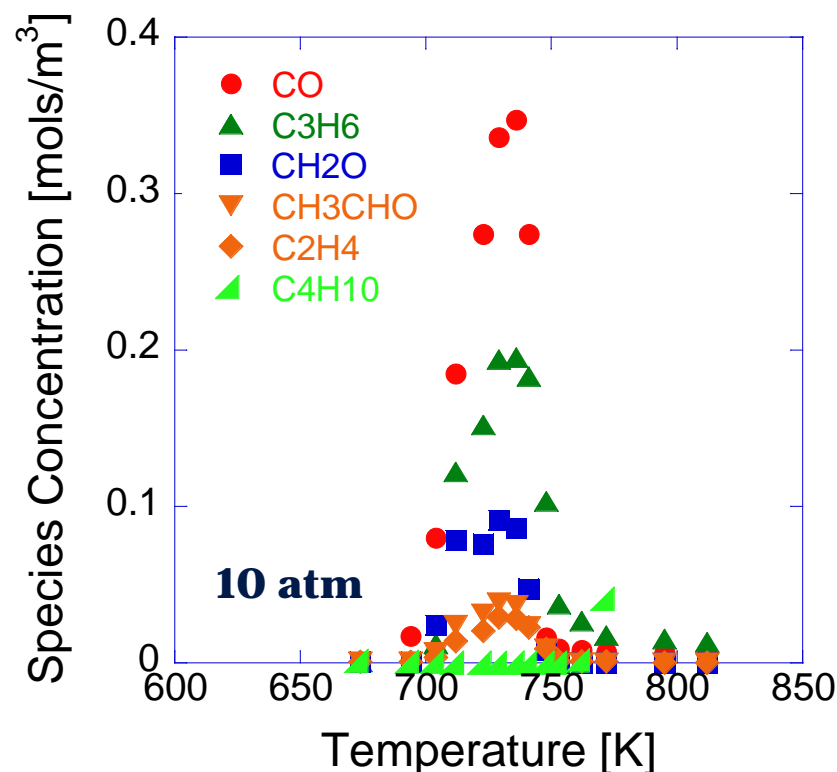
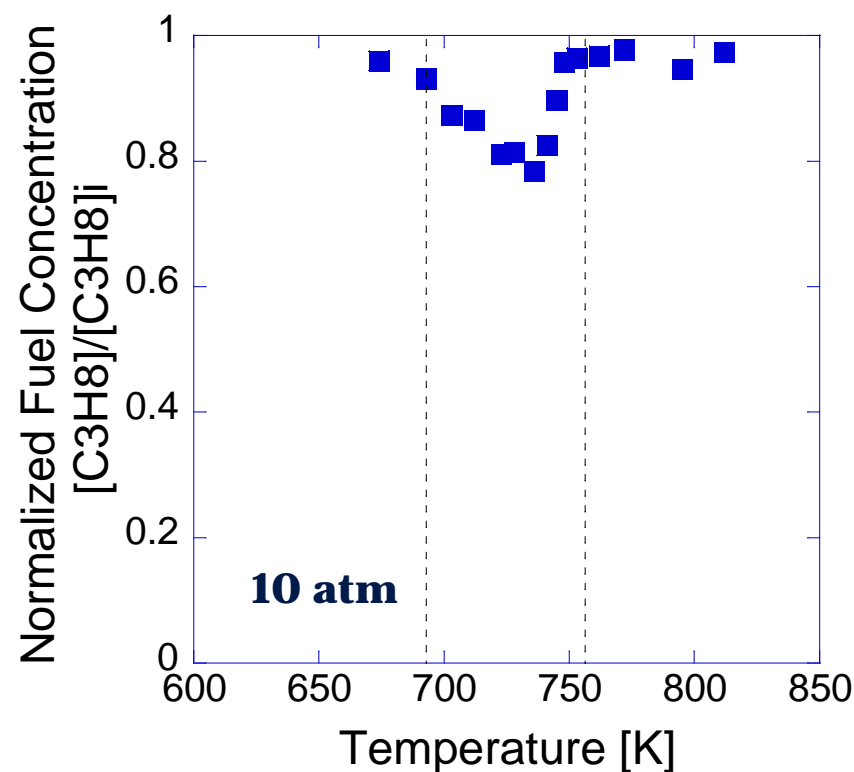


Kinetic Scheme of Primary Oxidation Reactions of n-Alkanes

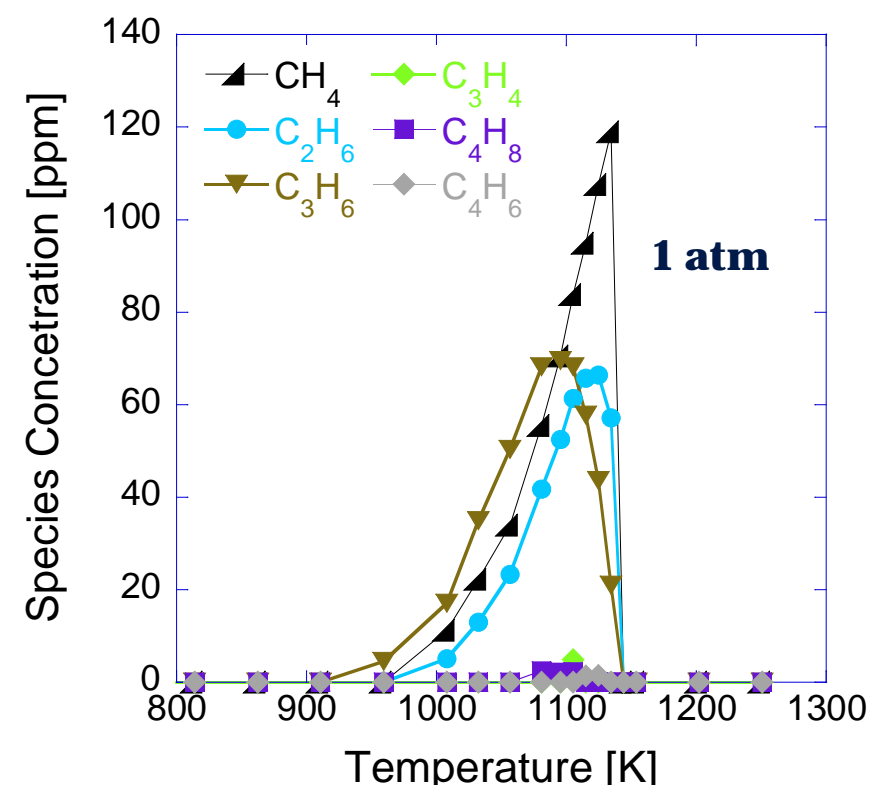
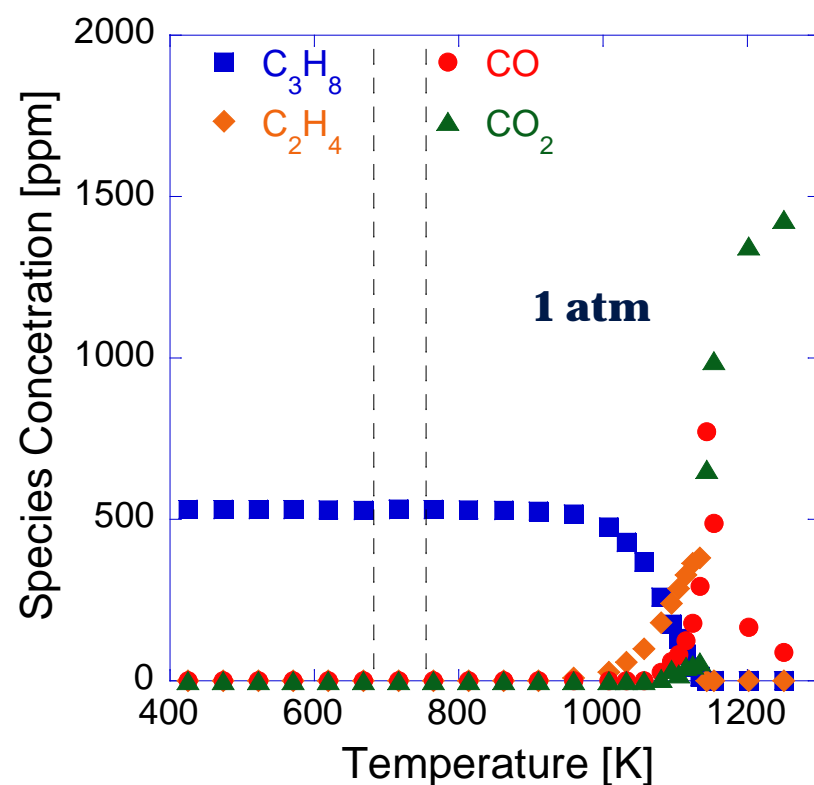


Thermal Oxidation of C_3H_8

D. N. Koert, D. L. Miller, and N. P. Cernansky, "Experimental Studies of Propane Oxidation through the Negative Temperature Coefficient Region at 10 and 15 Atmospheres," **Combustion and Flame**, 96, 34-49, 1994.



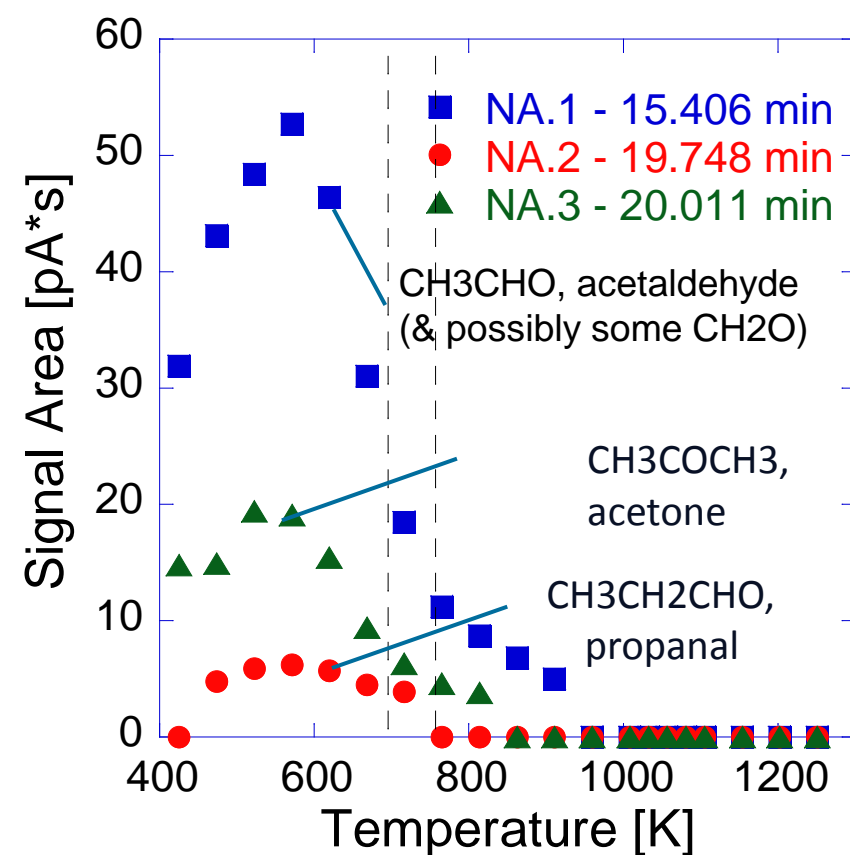
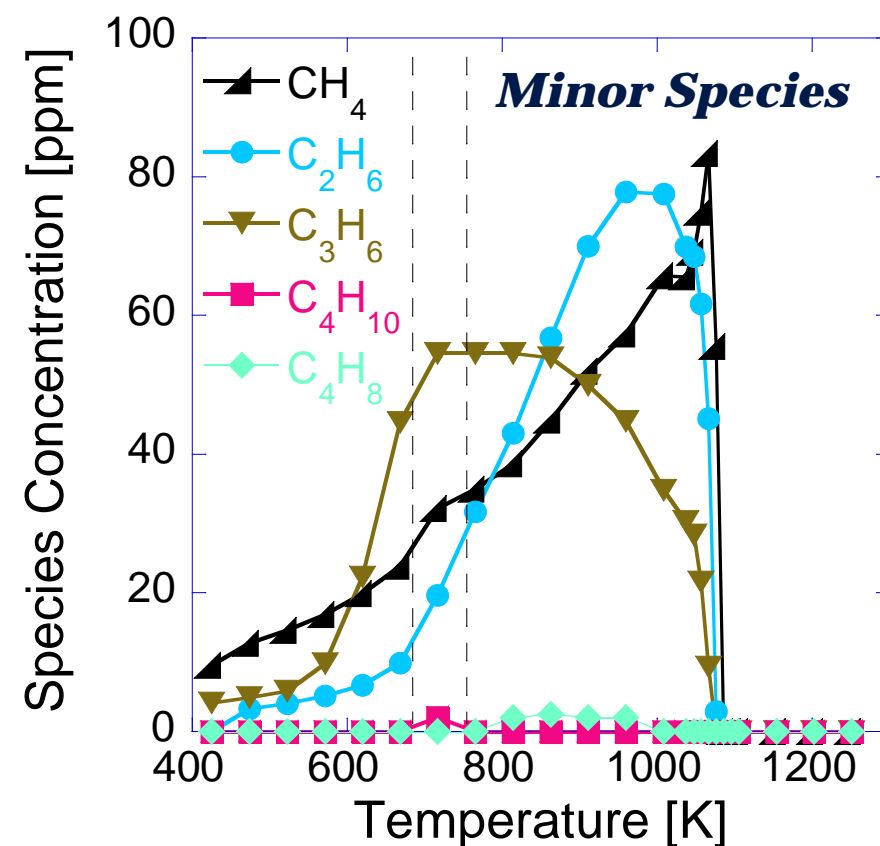
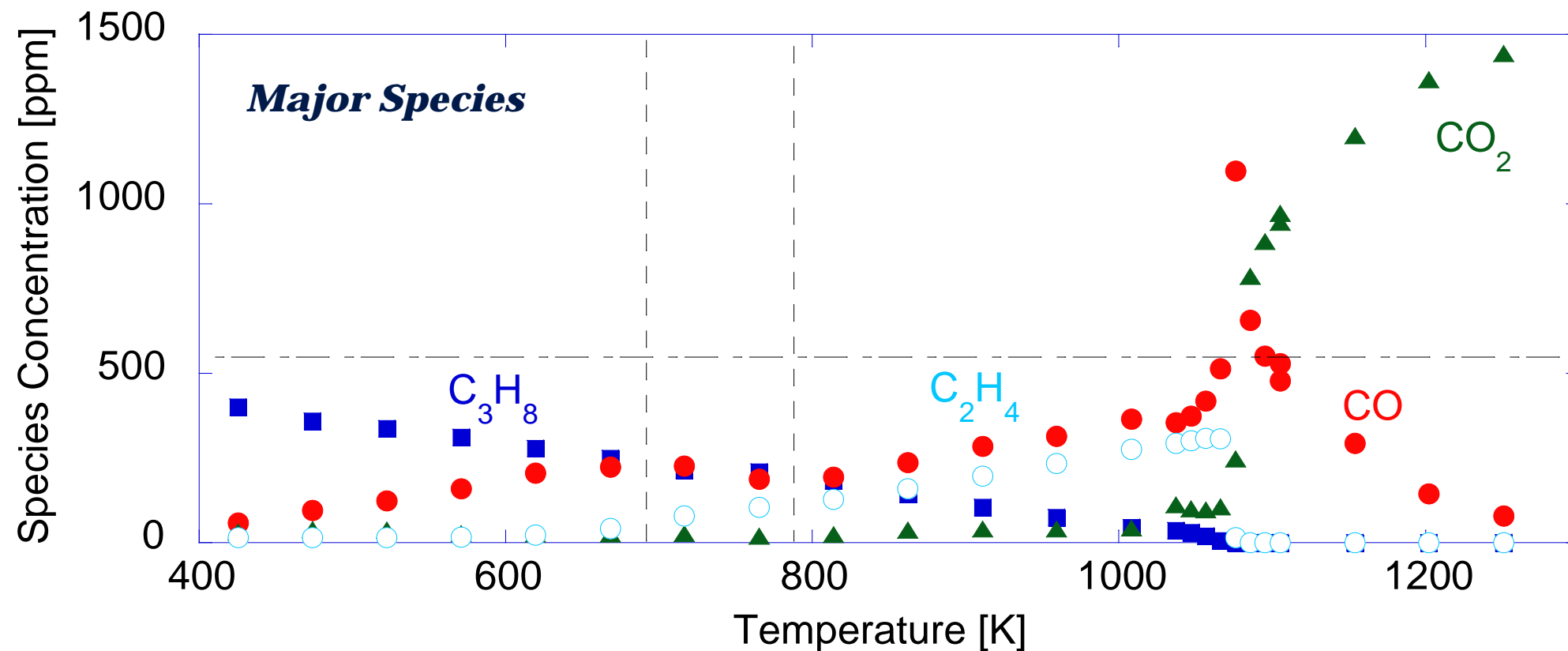
Experimental Conditions: P = 1 atm, Q = 1 LPM, 533ppm C_3H_8 /3000ppm O_2 / Ar balance



C₃H₈ Plasma Oxidation

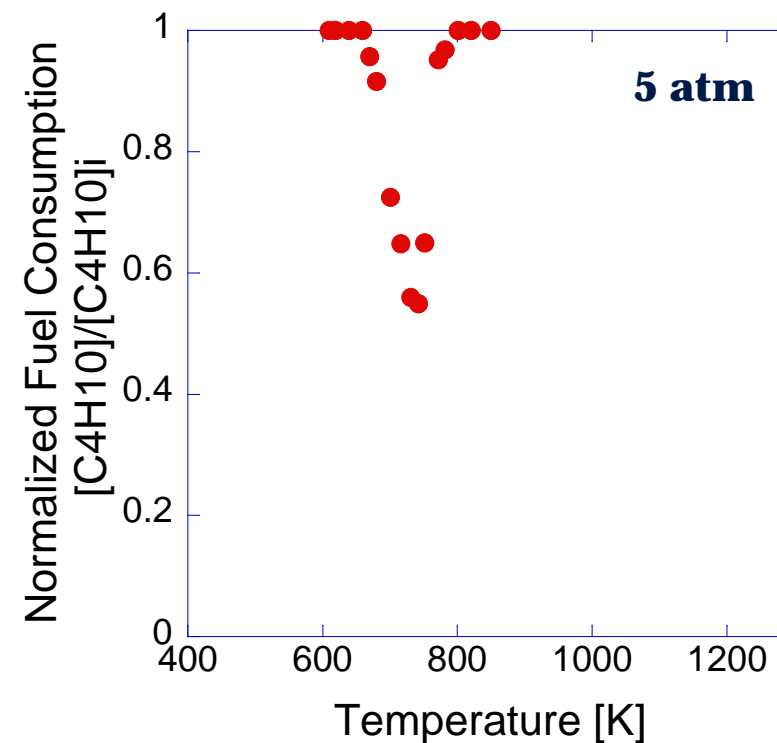
Experimental Conditions: P = 1 atm, Q = 1 LPM, 533ppm C₃H₈/3000ppm O₂ / Ar balance

Plasma Conditions: 10 kV, ν = 1 kHz

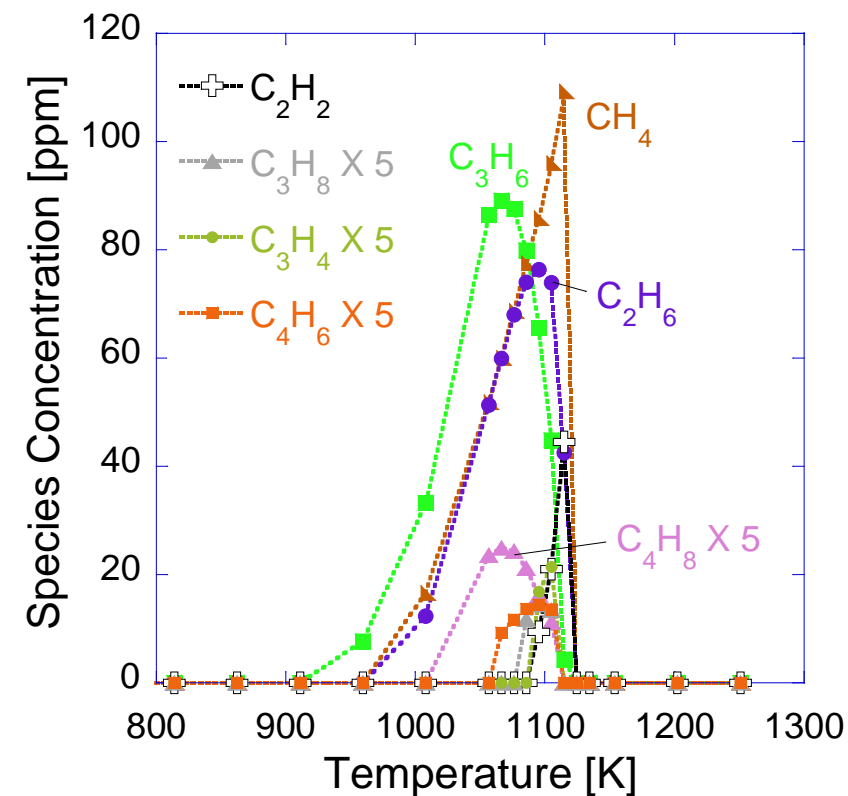
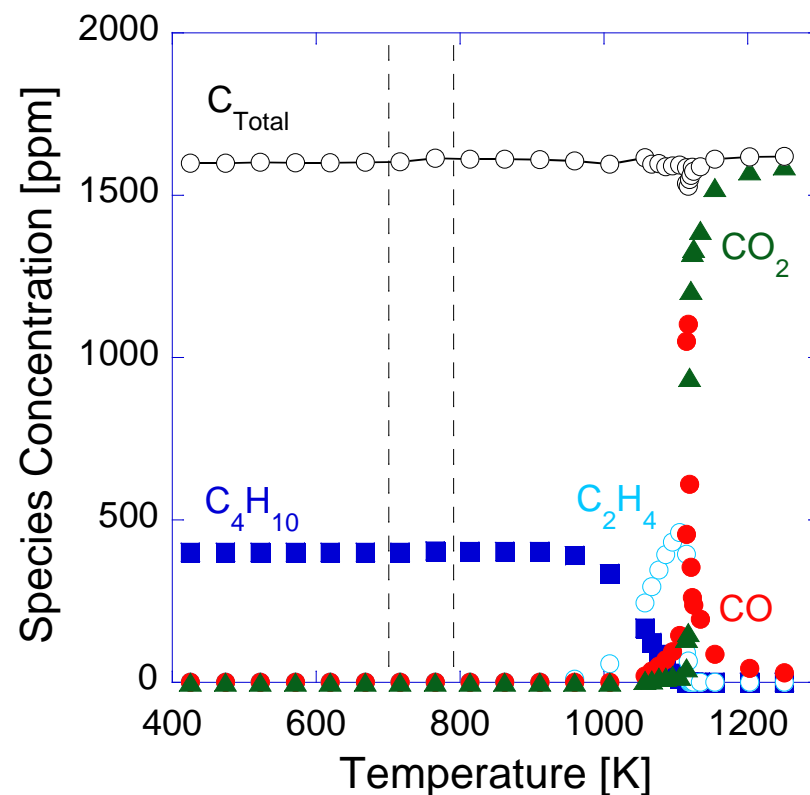


Thermal Oxidation of C₄H₁₀

Anand, A., "An Experimental Study of *n*-butane Oxidation at Elevated Pressures in the Low and Intermediate Temperature Regimes," **MS Thesis**, Drexel University, Philadelphia (1994).



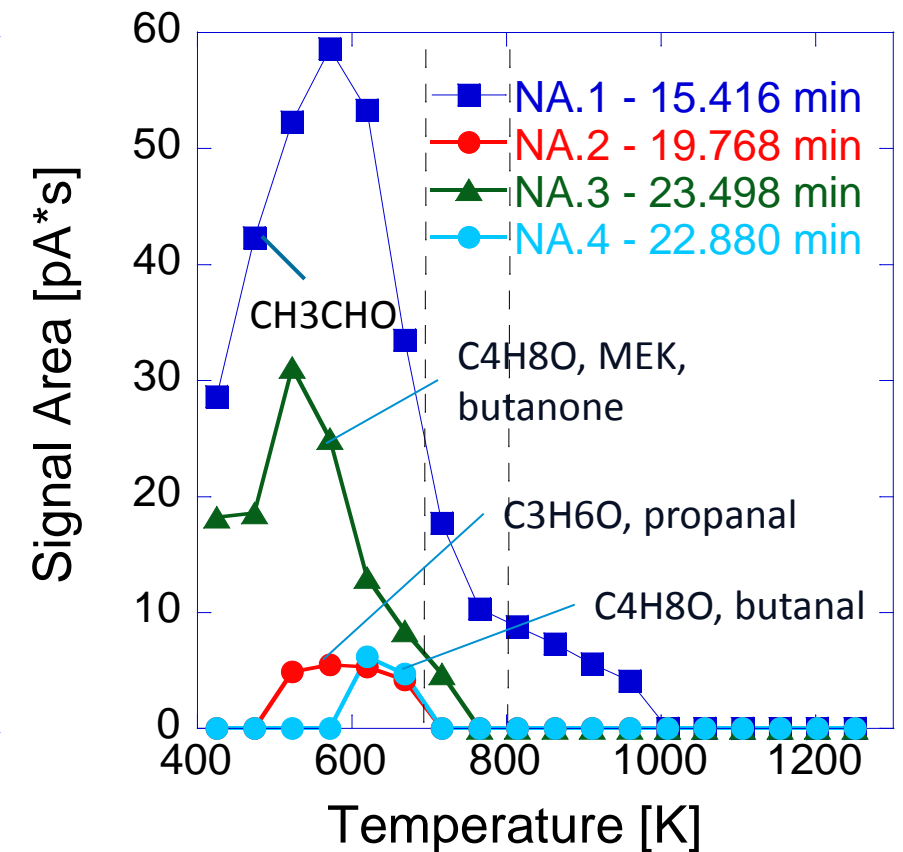
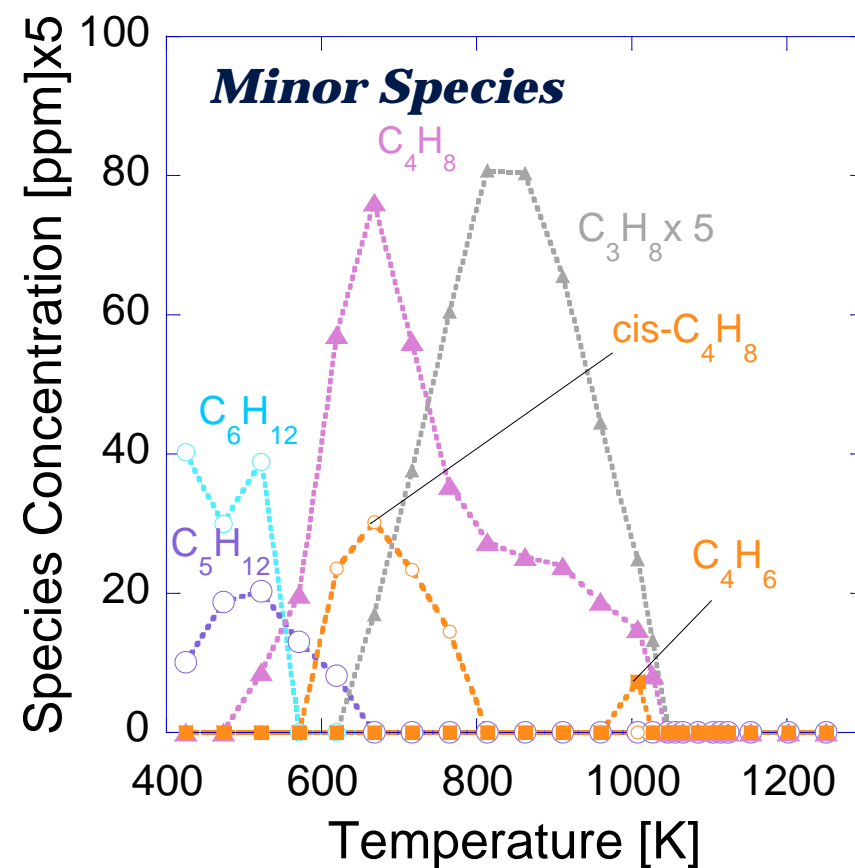
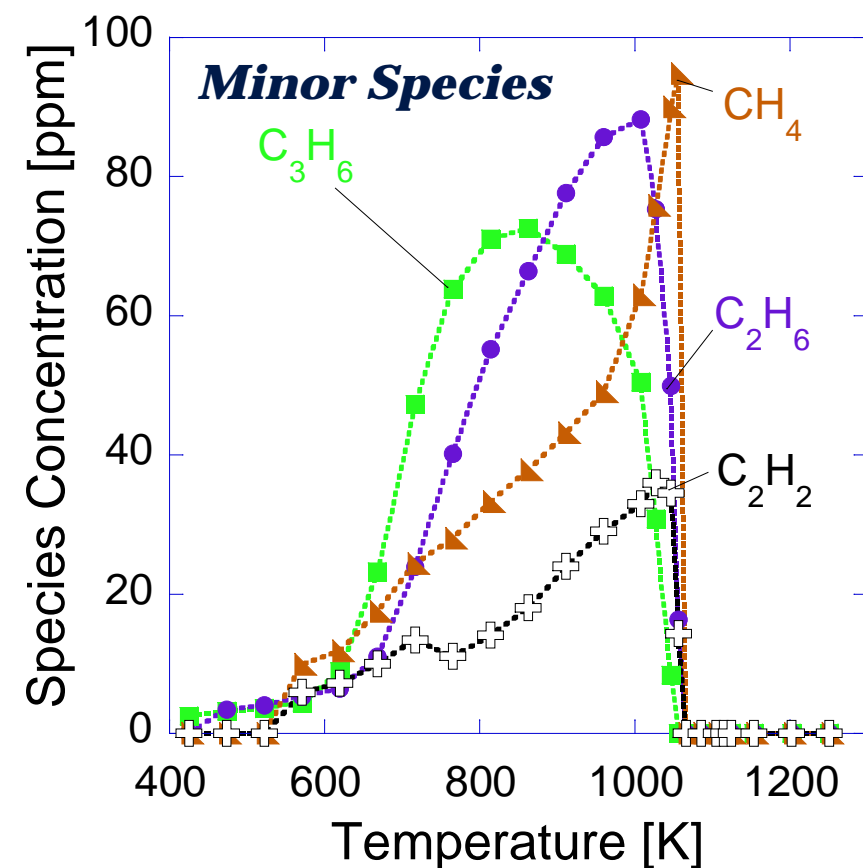
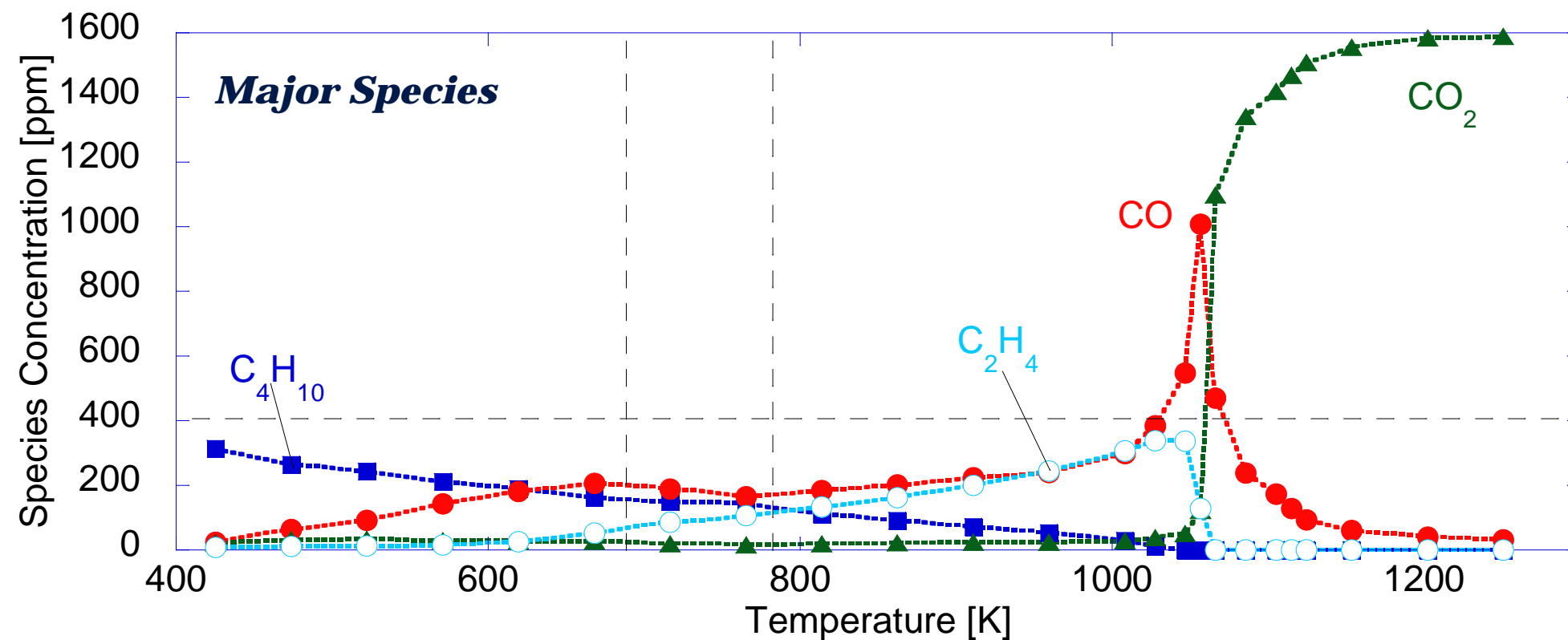
Experimental Conditions: $P = 1$ atm, $Q = 1$ LPM, 400ppm C₄H₁₀/3000ppm O₂ / Ar balance



C₄H₁₀ Plasma Oxidation

Experimental Conditions: P = 1 atm, Q = 1 LPM, 400ppm C₄H₁₀/3000ppm O₂ / Ar balance

Plasma Conditions: 10 kV, ν = 1 kHz



H₂ Plasma Assisted Oxidation



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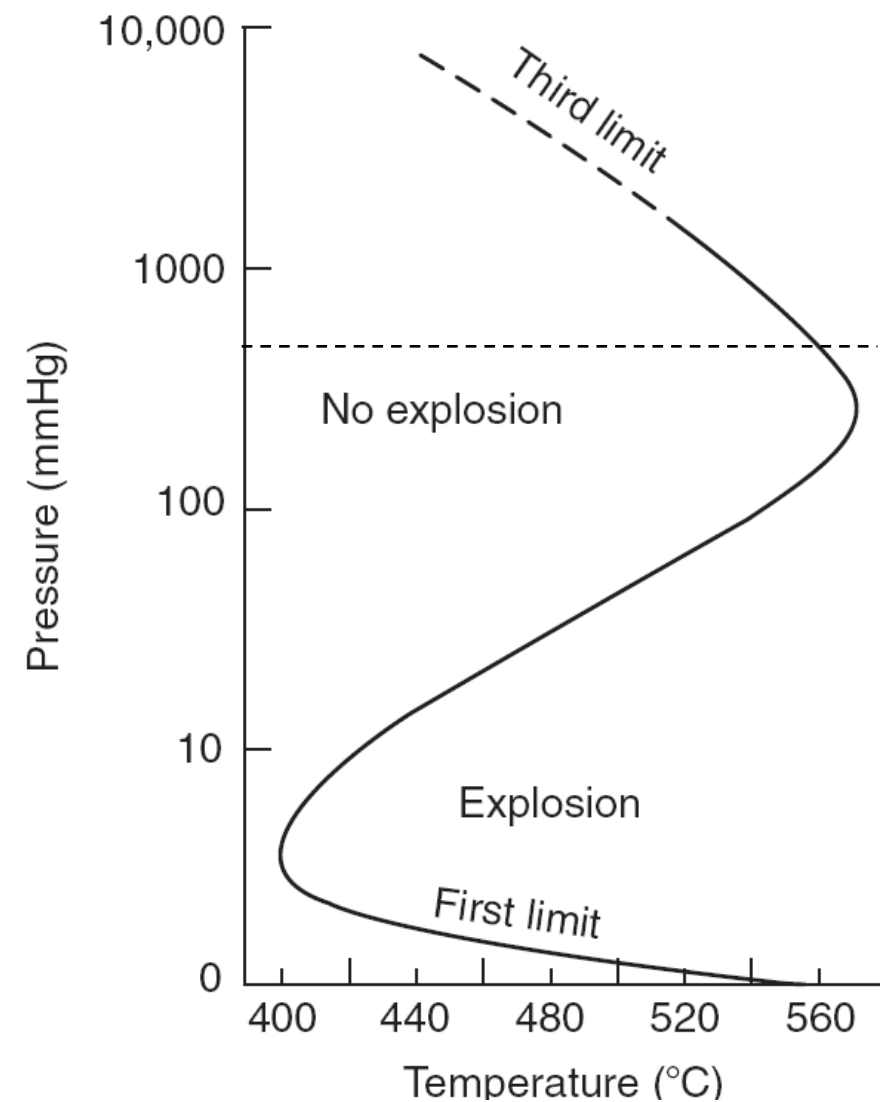
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H₂ Thermal and Plasma Assisted Oxidation

Experimental Conditions: P = 1 atm, Q = 1 LPM, 2000ppm H₂/3000ppm O₂ / Ar balance

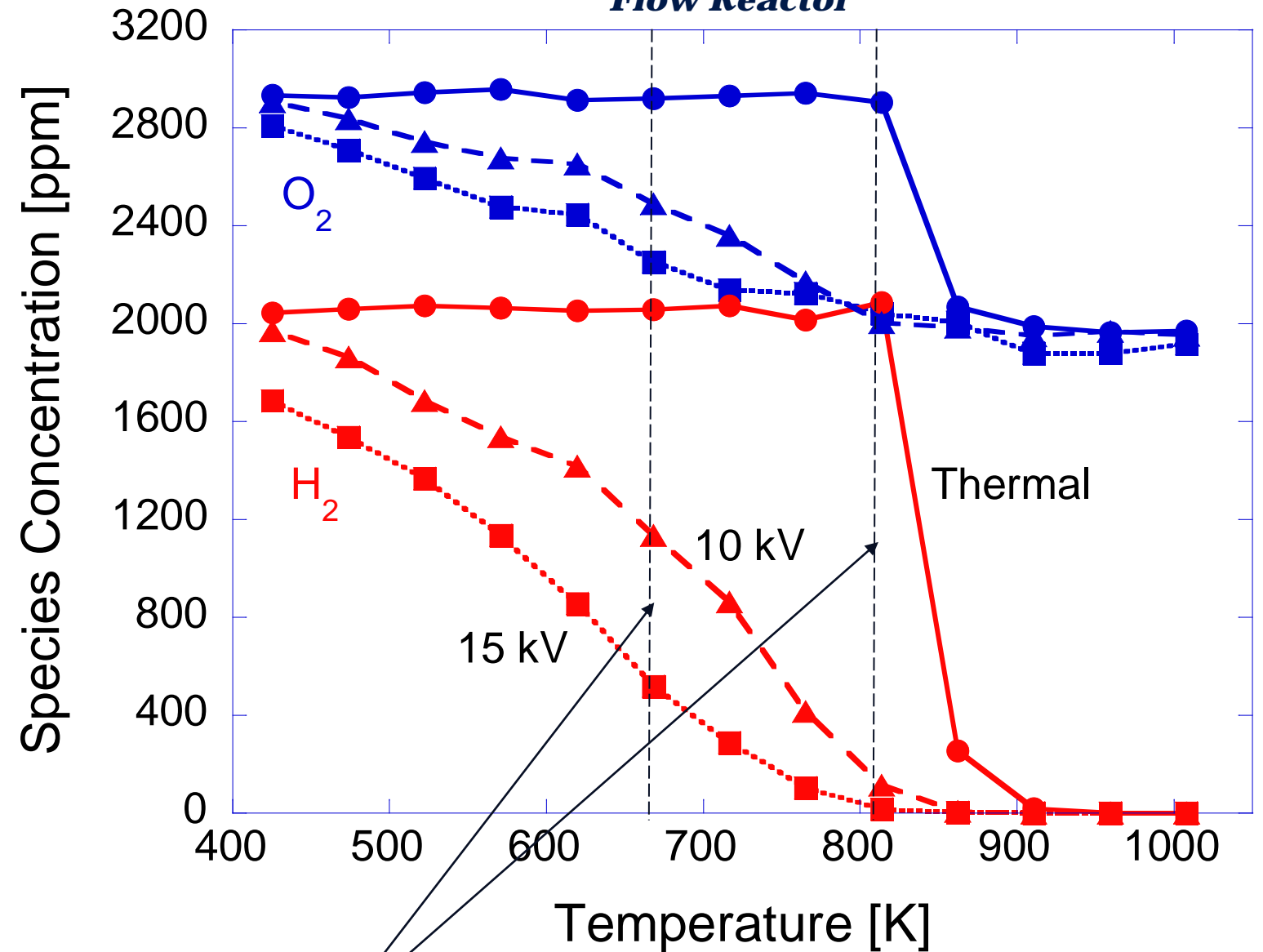
Plasma Conditions: 10kV and 15 kV, $\nu = 1$ kHz

H₂/O₂ Explosion Limits



I. Glassman and R.A. Yetter, **Combustion**,
4th Ed, Academic Press, 2008

Flow Reactor



**OH LIF Experiments @ $T = 668K$
and $T = 814K$**



0D Kinetics Model with Sensitivity Analysis

SENKIN (CHEMKIN)

- Calculate $k(T)$
- Time integration
- Isothermal region modeled as constant T and P process
- Temperature ramps currently not included
- Plug flow assumption

$$k = AT^n \exp(-E_a/RT)$$

$$\frac{\partial N_i}{\partial t} = \omega_i$$

ZDPlasKin, a Boltzmann equation solver (University of Toulouse, LAPLACE, 2008)

- Calculate rates for electron-impact reactions
- Electron impact cross sections are fed
- Calculate v_{drift}

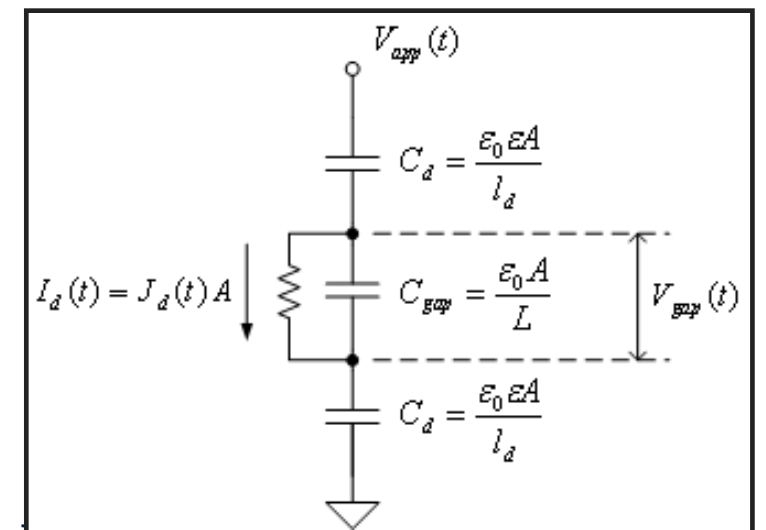
Circuit module

- Calculate E/N
- Assumed homogeneity across discharge planes

$$\frac{E}{N} = \frac{V_{\text{gap}}(t)/L}{N}$$

$$J_p = eN_e v_{\text{drift}}$$

$$\frac{dV_{\text{gap}}(t)}{dt} = \left(1 + \frac{2l_d}{\varepsilon L}\right)^{-1} \left(\frac{dV_{\text{app}}(t)}{dt} - \frac{2l_d}{\varepsilon_0 \varepsilon} J_p(t) \right)$$



Preliminary H₂ Chemical Reaction Mechanism (39 species, 527 reactions)

Electron-impact reactions (Van Gaens and Bogaerts, 2013 and Kossyi et al., 1992)

Excitation, Deexcitation, Dissociation, Ionization, Recombination

Excited and ionized species (Van Gaens and Bogaerts, 2013, Kossyi et al., 1992 and Popov, 2011)

Ar/H/O atoms

Neutral, ground state species

H₂/O₂ Mechanism (Popov, 2008), O₃ Chemistry (Bromly et al., 1996)

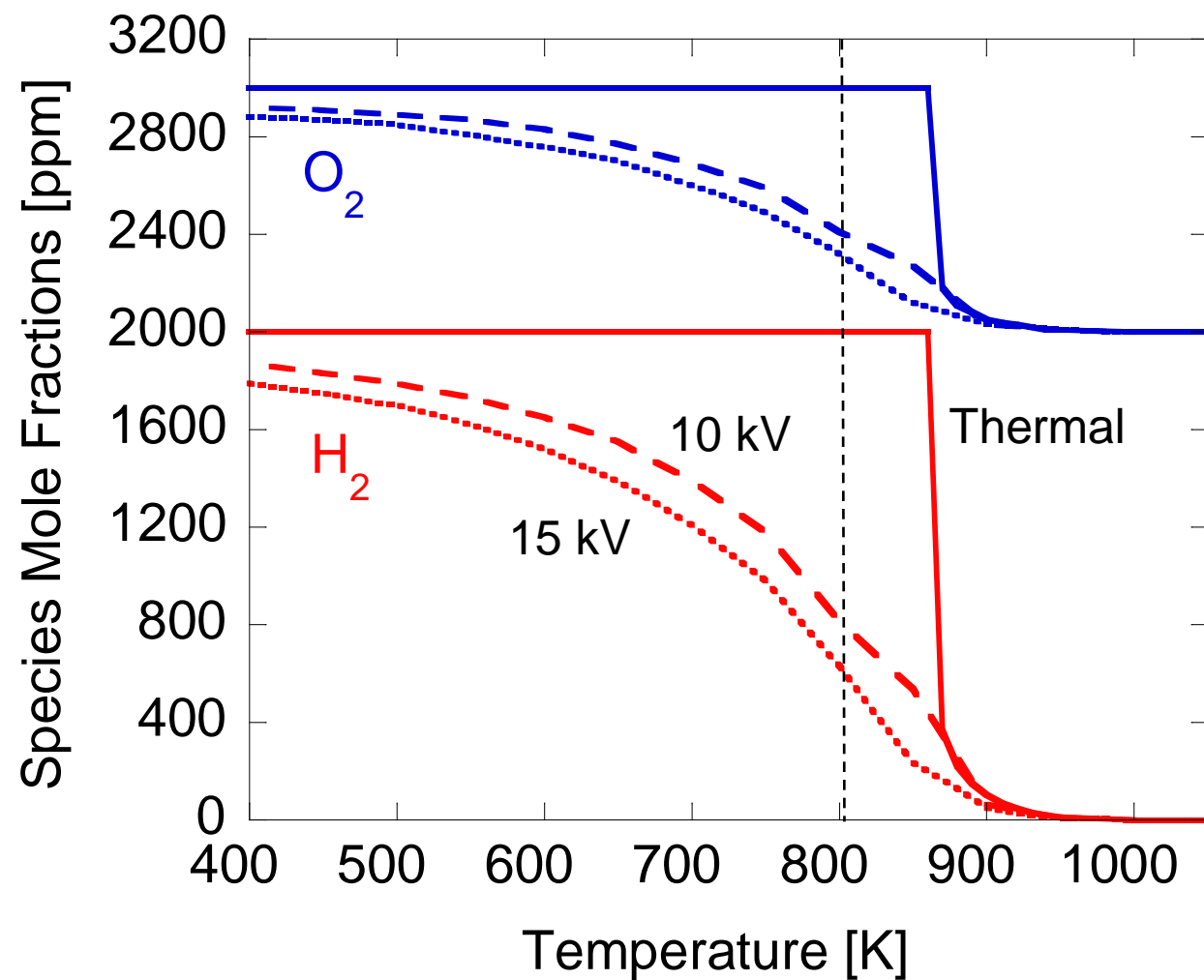
Wall quenching of positive ions



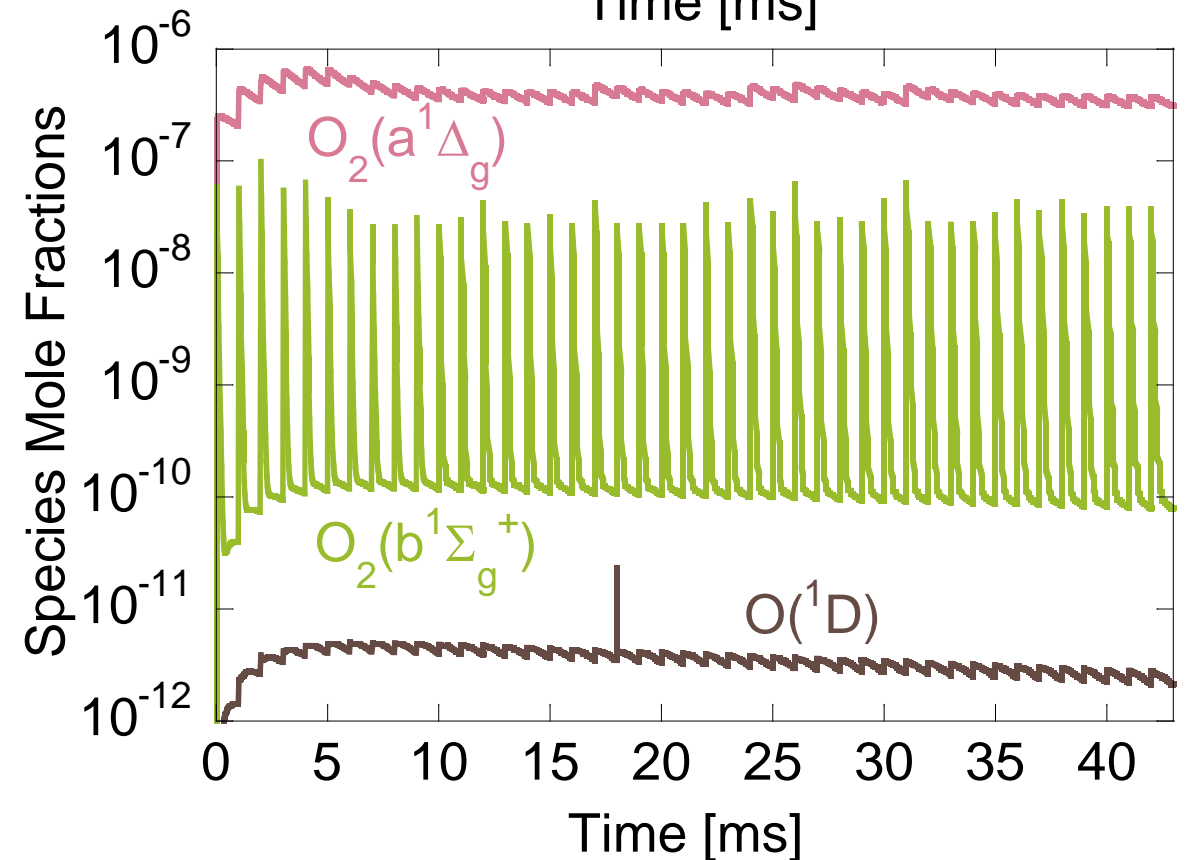
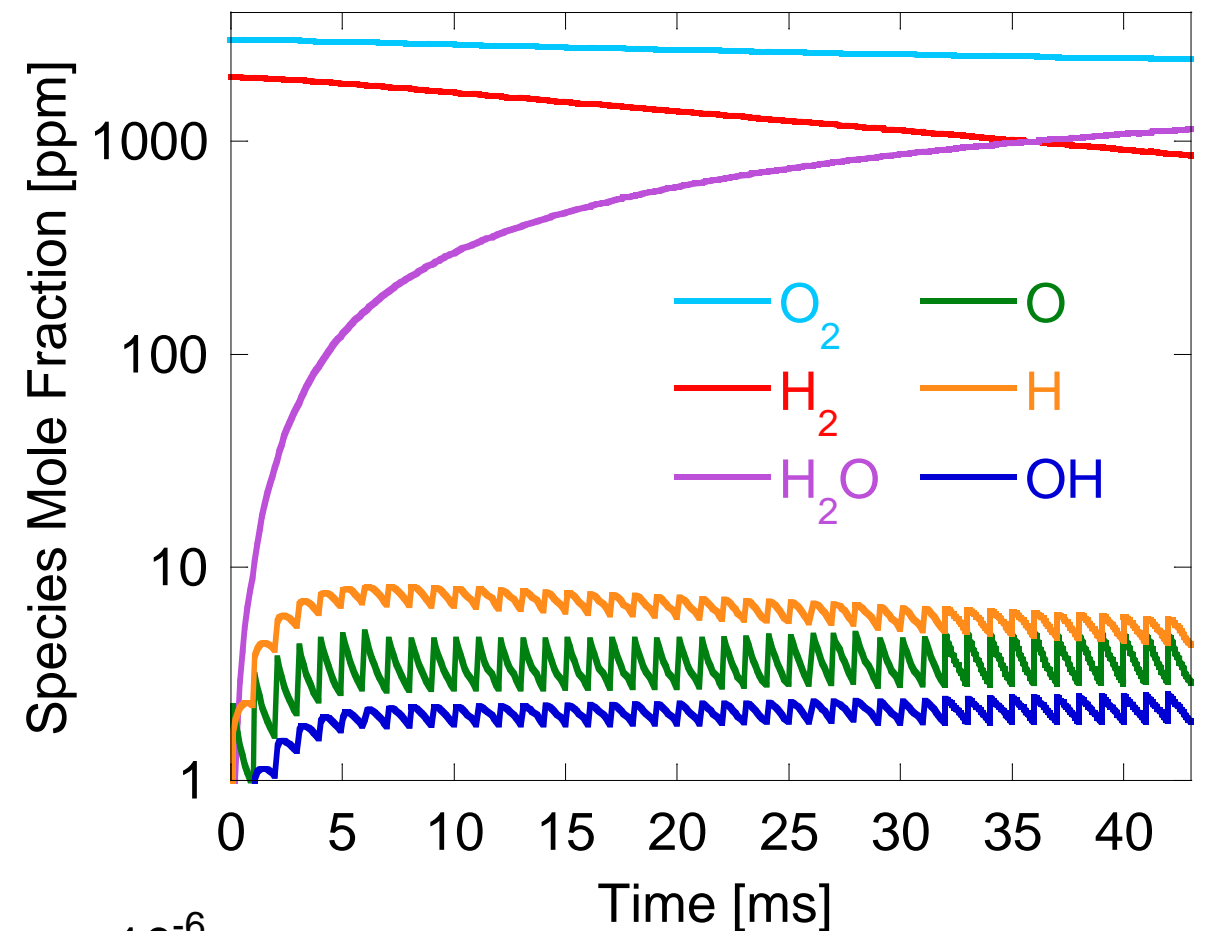
H₂ Oxidation (0D Kinetic Model)

Conditions: P = 1 atm, Q = 1 LPM, 2000ppm H₂/3000ppm O₂ / Ar balance

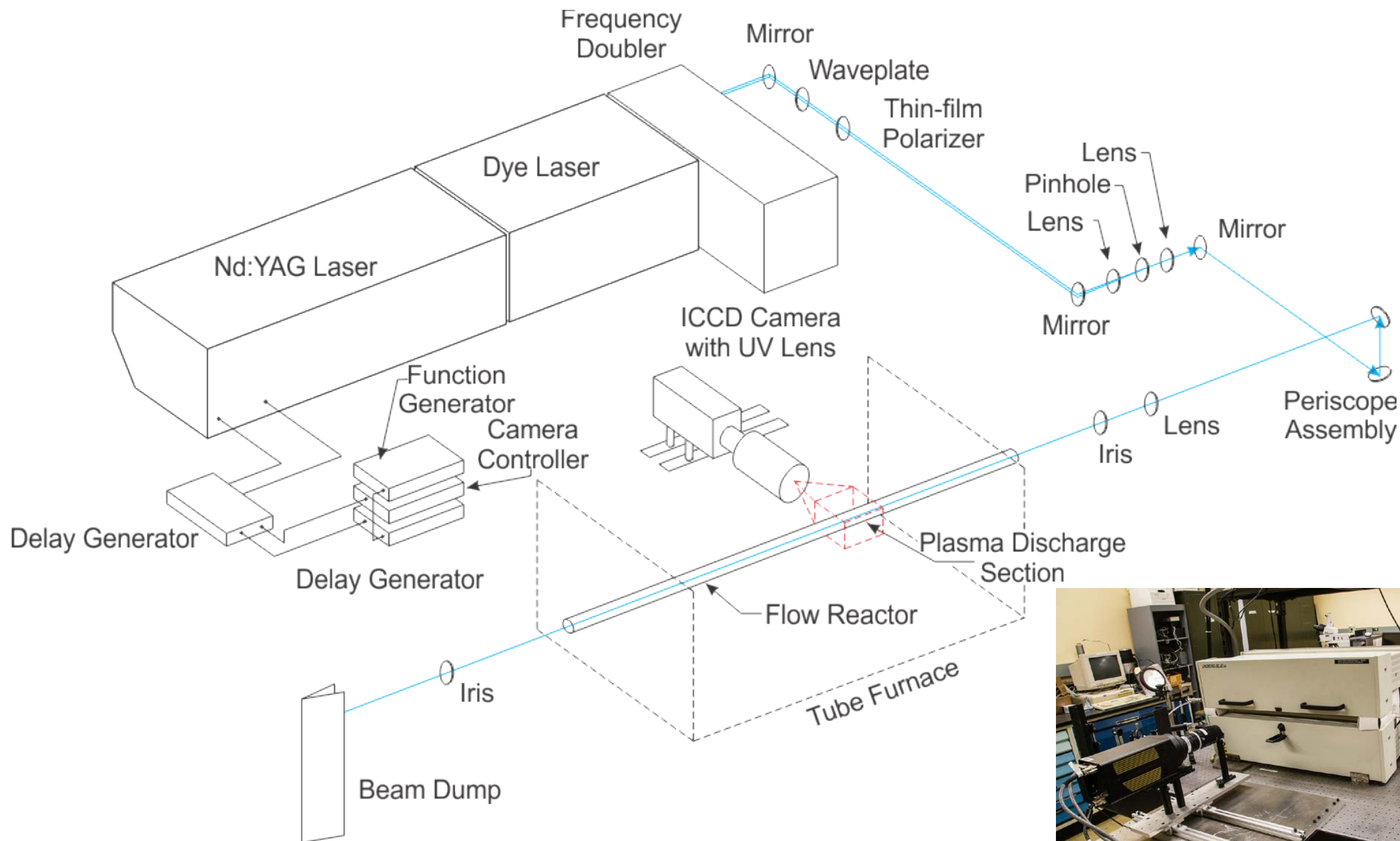
Plasma Conditions: 10kV and 15 kV, $\nu = 1$ kHz



T = 800K, 10kV, $\nu = 1$ kHz
Electrode Region



OH LIF Experimental Extension

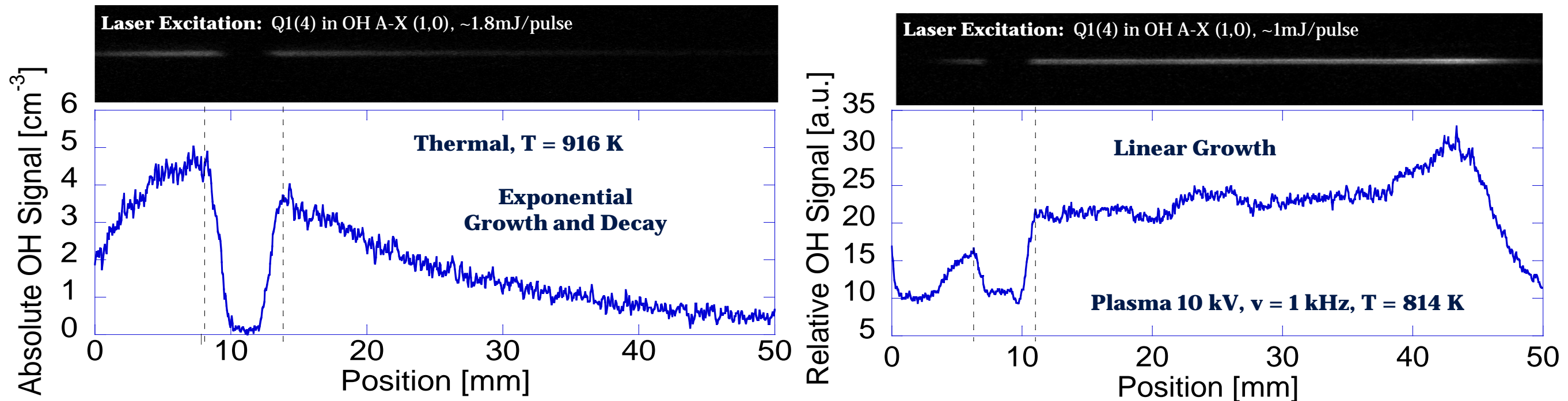


- *in-situ* OH LIF implemented into existing flow reactor experiment in collaboration with OSU group (Zhiyao Yin and Kraig Frederickson)
- ICCD camera mounted on **translational stage** to obtain measurements along the length of the reaction zone

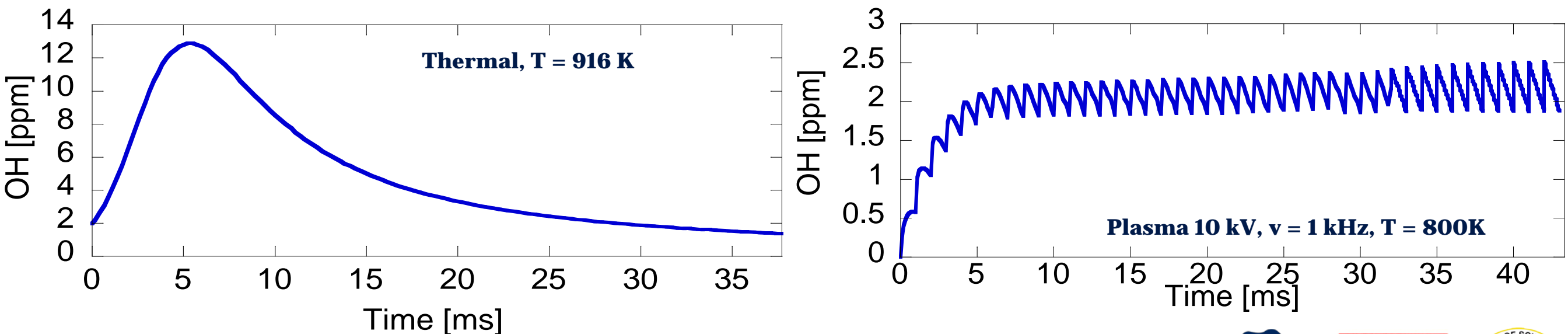


OH LIF Experiments

Experimental Conditions: $P = 1$ atm, $Q = 1$ LPM, 2000 ppm H_2 /3000ppm O_2 / Ar balance
600 Shots On- ICCD Accumulations



OH OD Plasma Chemical Kinetics Code

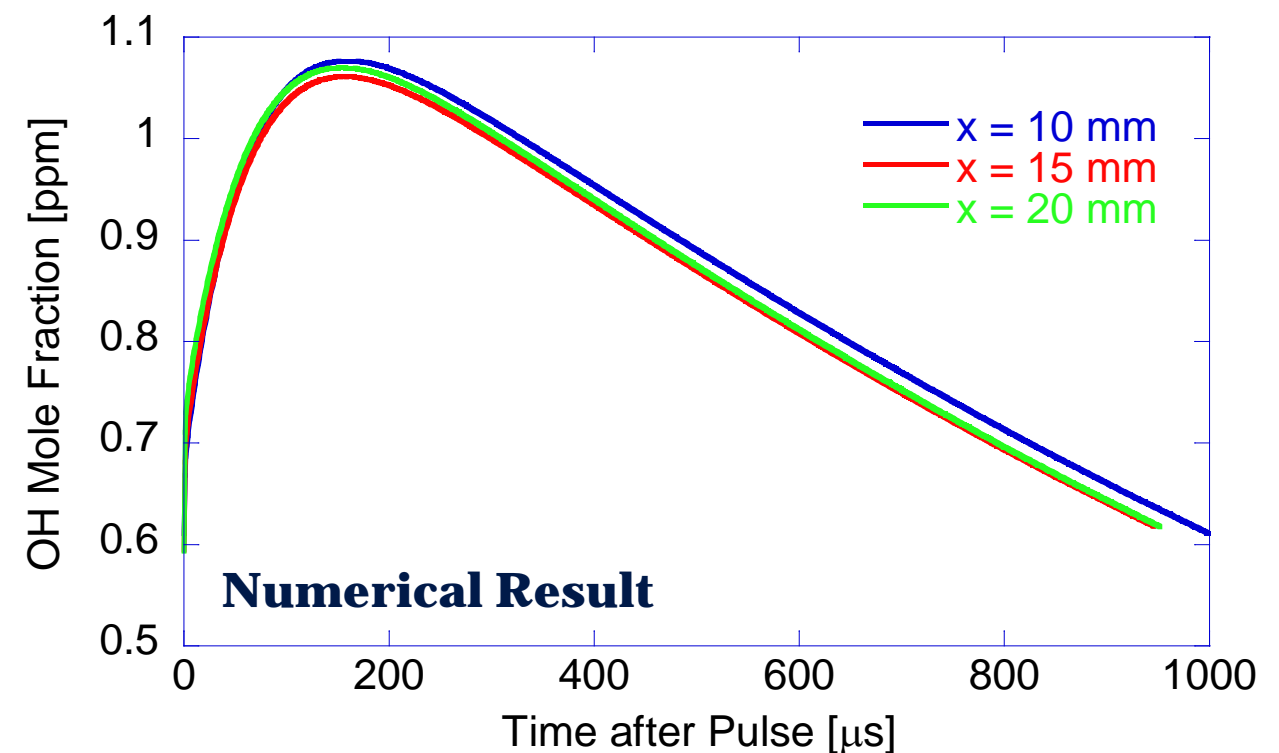
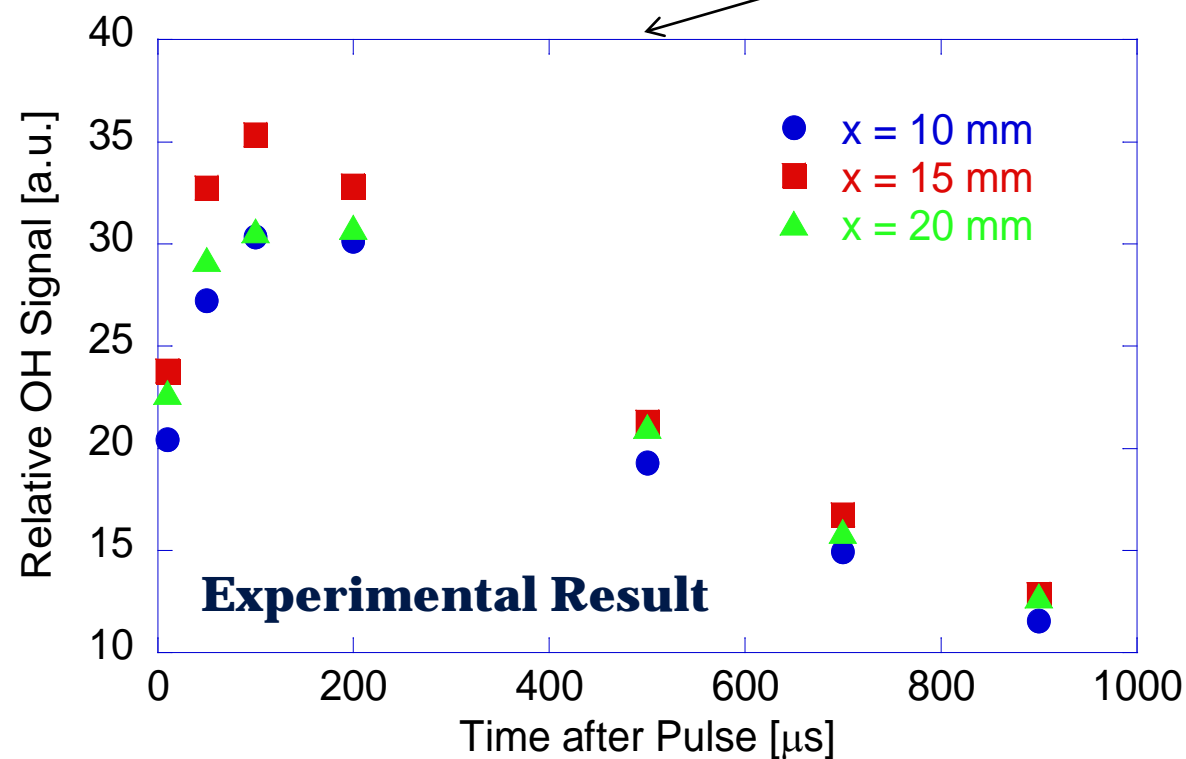
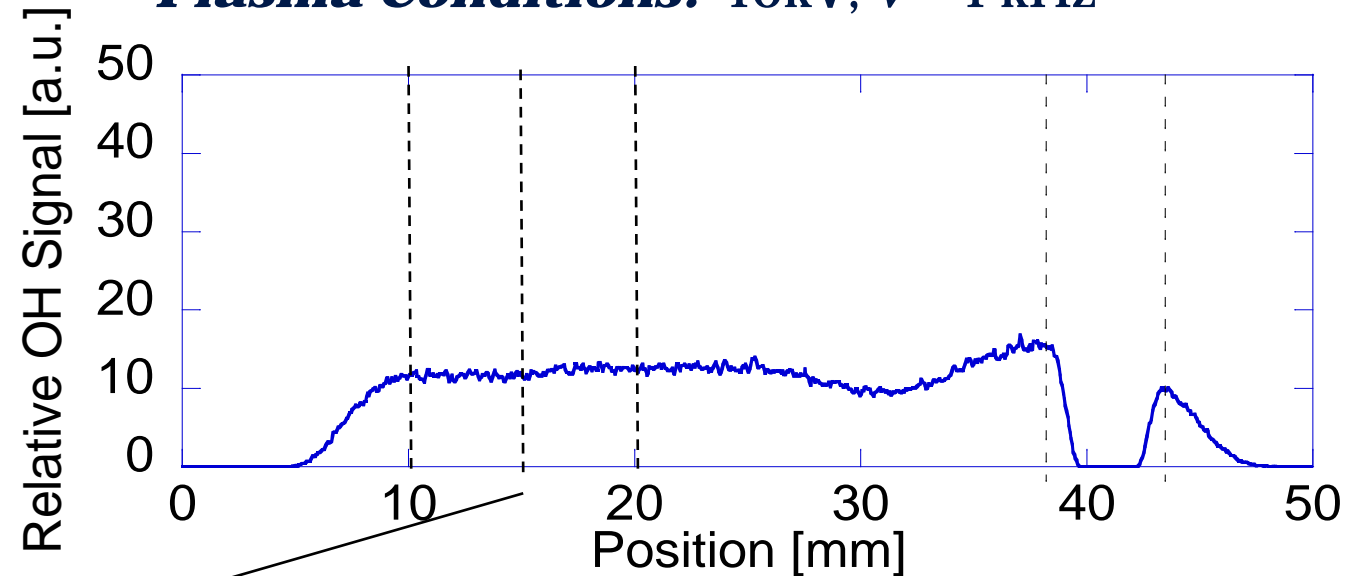


Transient Behavior of OH at a Specific Reactor Location

Conditions: $P = 1$ atm, $T = 668$ K, $Q = 1$ LPM, 2000ppm H_2 /3000ppm O_2 / Ar by balance

Plasma Conditions: 10kV, $\nu = 1$ kHz

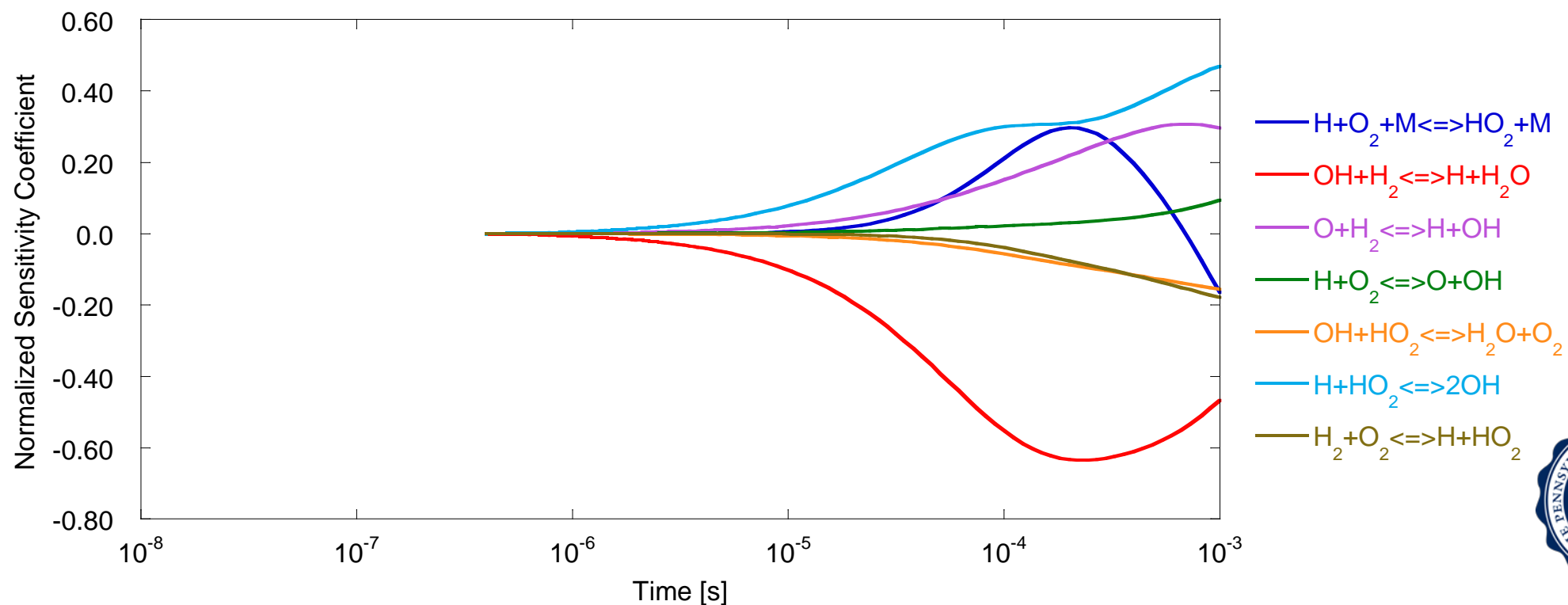
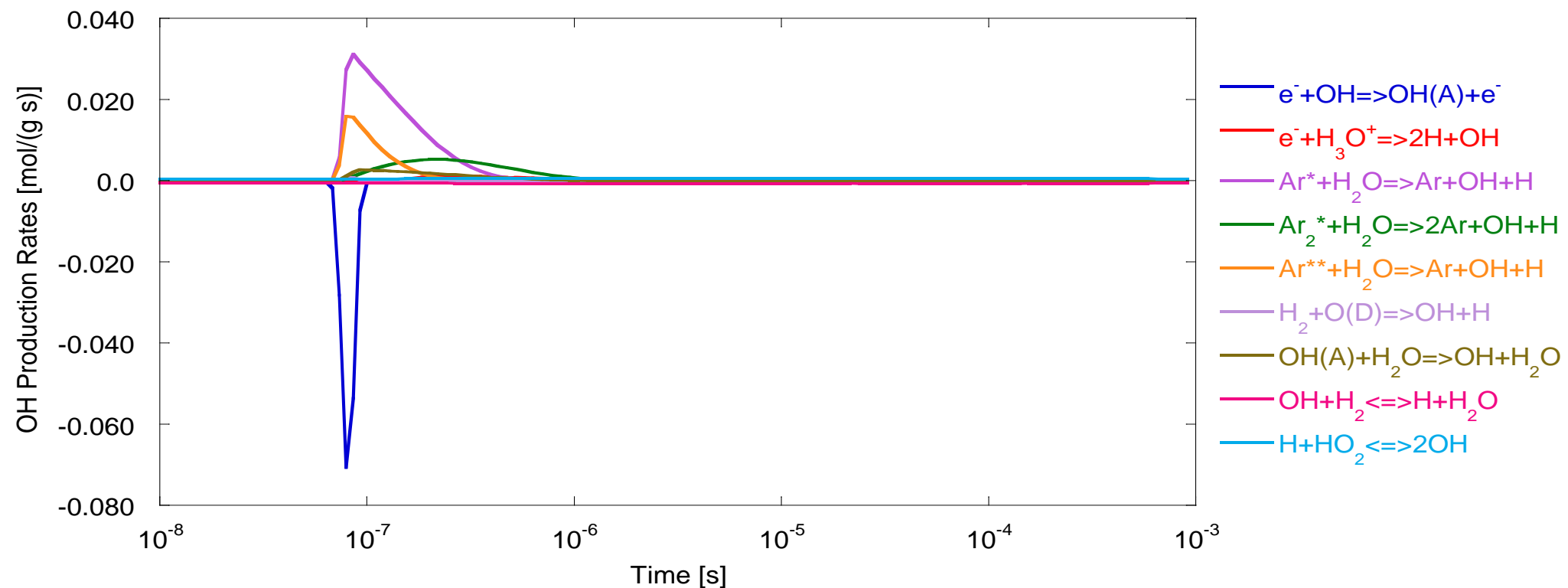
**Example of
Experimental OH
Signal
@ $t = 900 \mu s$**



OH Production and Sensitivity

Conditions: P = 1 atm, T=800 K, Q = 1 LPM, 2000ppm H₂/3000ppm O₂ / Ar by balance
Plasma Conditions: 10kV, $\nu = 1$ kHz

Pulse #22
 Discharge at 77 ns, V_{peak} at 100 ns



Summary

- Alkane (C1-C7) oxidation has been studied with and without plasma enhancement:
 - Fuel consumption across $T = 420 - 1250$ K has been significantly enhanced for all fuels, the plasma also lowers the temperature for complete fuel consumption (*the temperature for onset of high temperature ignition*)
 - Experimental results indicate an extension of RO2 low temperature (cool flame) chemistry to lower pressures (*identification/quantification of select species will be improved i.e., aldehydes*)
- H2 oxidation has been studied with and without plasma enhancement:
 - H2 and O2 consumption measured *ex-situ* GC analysis, modifications to the current facility have been made to perform *in-situ* OH LIF measurements in conjunction with OSU group
 - Zero-D plasma kinetic model has been developed based on SENKIN to derive detailed sensitivity analysis
 - Qualitative comparisons of model and experiment indicate current plasma assisted combustion models for hydrogen oxidation perform well.
- Experiment and model analysis of low temperature C2H4/N2/O2/Ar mixtures suggest intermediate formation of nitromethane. Formation of such nitro and nitrate compounds at low temperatures may be a means to enhance ignition.



Team Interactions/Collaborations

- Collaborative research with Ohio State on plasma kinetic modeling of PSU pyrolysis and oxidation experiments.
- Collaborative research with Ohio State on *in-situ* OH LIF measurements.
- Plasma Assisted Combustion MURI Kinetics Working Group



Secondary Slides

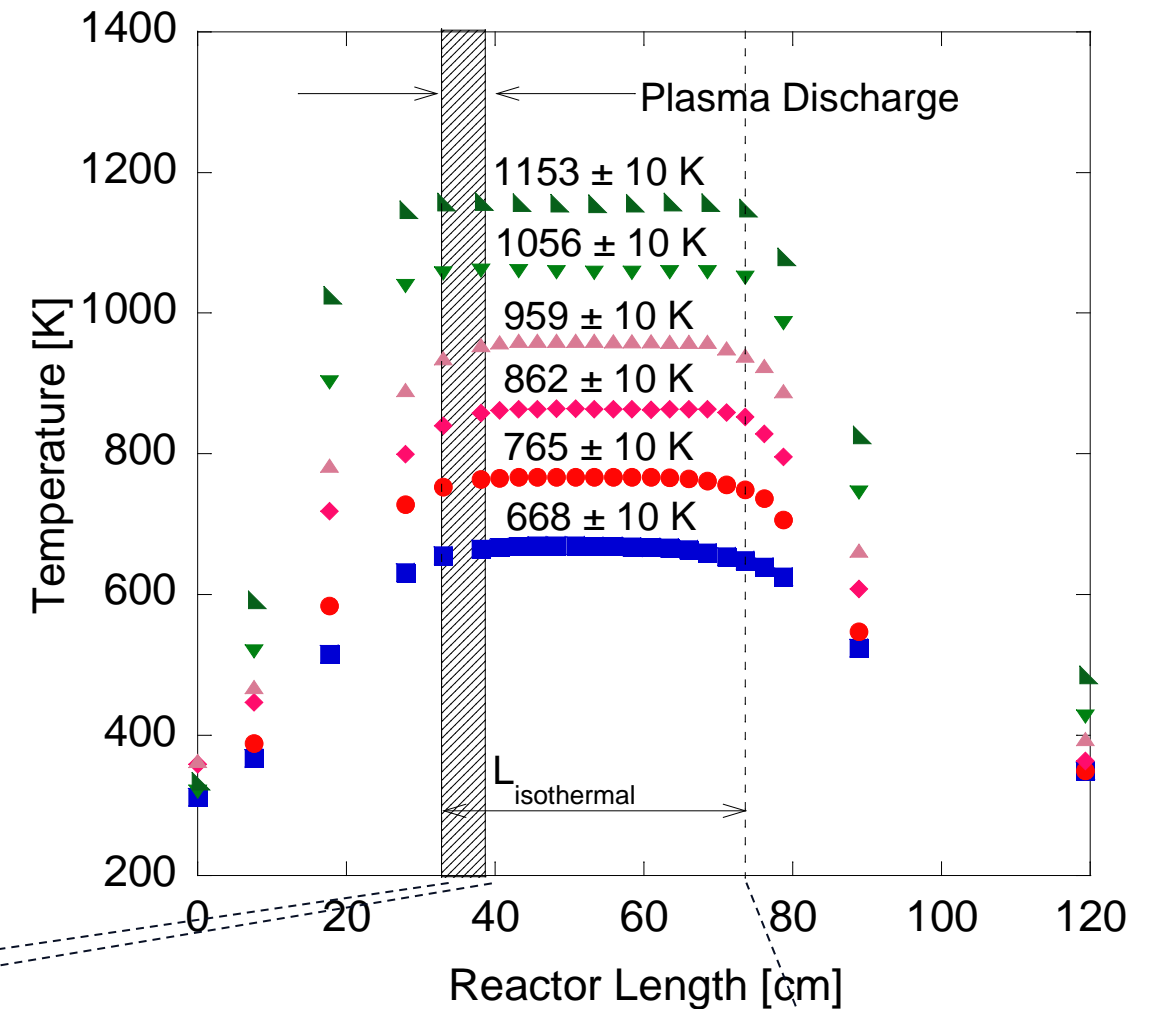


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22-24th October 2013, Basic Research Innovation Collaboration Center, Arlington, VA

0D Kinetics Model

- **Isothermal** region modeled as *constant Temperature and Pressure* process
- Temperature ramps ignored (*to be implemented in the future*)
- Assumed **homogeneity** across discharge planes
- **Plug flow** assumption
- Convert **distance to time** based on experimental flow rate



Preliminary Chemical Reaction Mechanism

114 species, 1461 reactions

- Electron-impact reactions (Mainly from Van Gaens and Bogaerts, 2013 and Kossyi *et al.*, 1992)
 - Excitation
 - Deexcitation
 - Dissociation
 - Ionization
 - Recombination
- Excited and ionized species (Mainly from Van Gaens and Bogaerts, 2013 and Kossyi *et al.*, 1992)
 - Ar/H/N/O atoms
- Interactions of hydrocarbons with excited species
- Neutral, ground state species
 - Hydrocarbon oxidation (Bromly *et al.*, 1996)
 - NO_x Mechanisms
 - Zel'dovich (Bromly *et al.*, 1996)
 - Prompt, N₂O and NNH (GRI-Mech 3.0)

Plasma Effects on NO_x Formation at Various Temperatures

50% Ar / 50% Air

p = 1 atm

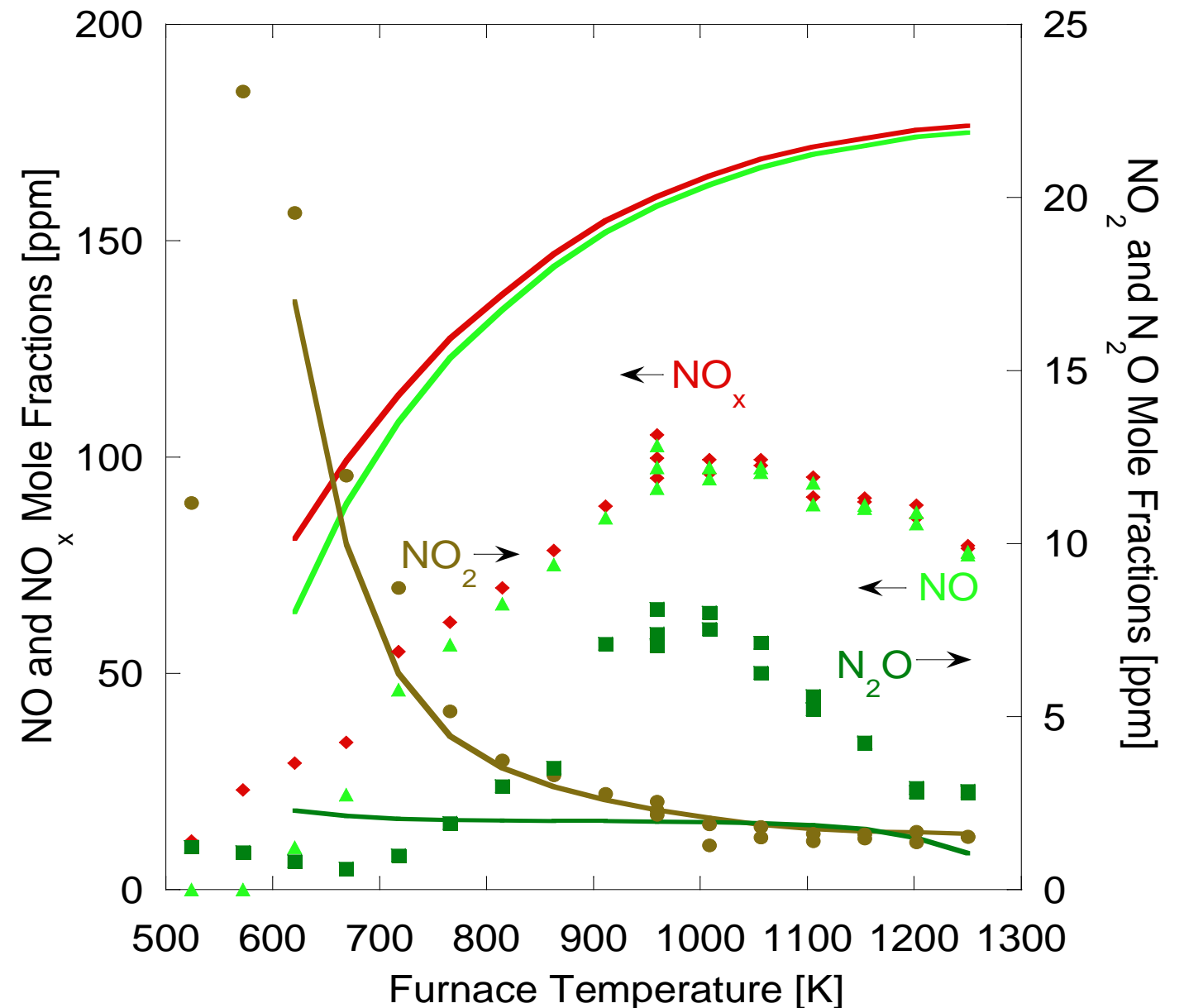
Plasma residence time, $\tau_{\text{plasma}} = 100$ ms

$V_{\text{peak}} = 15$ kV

Repetition rate, $f = 1$ kHz

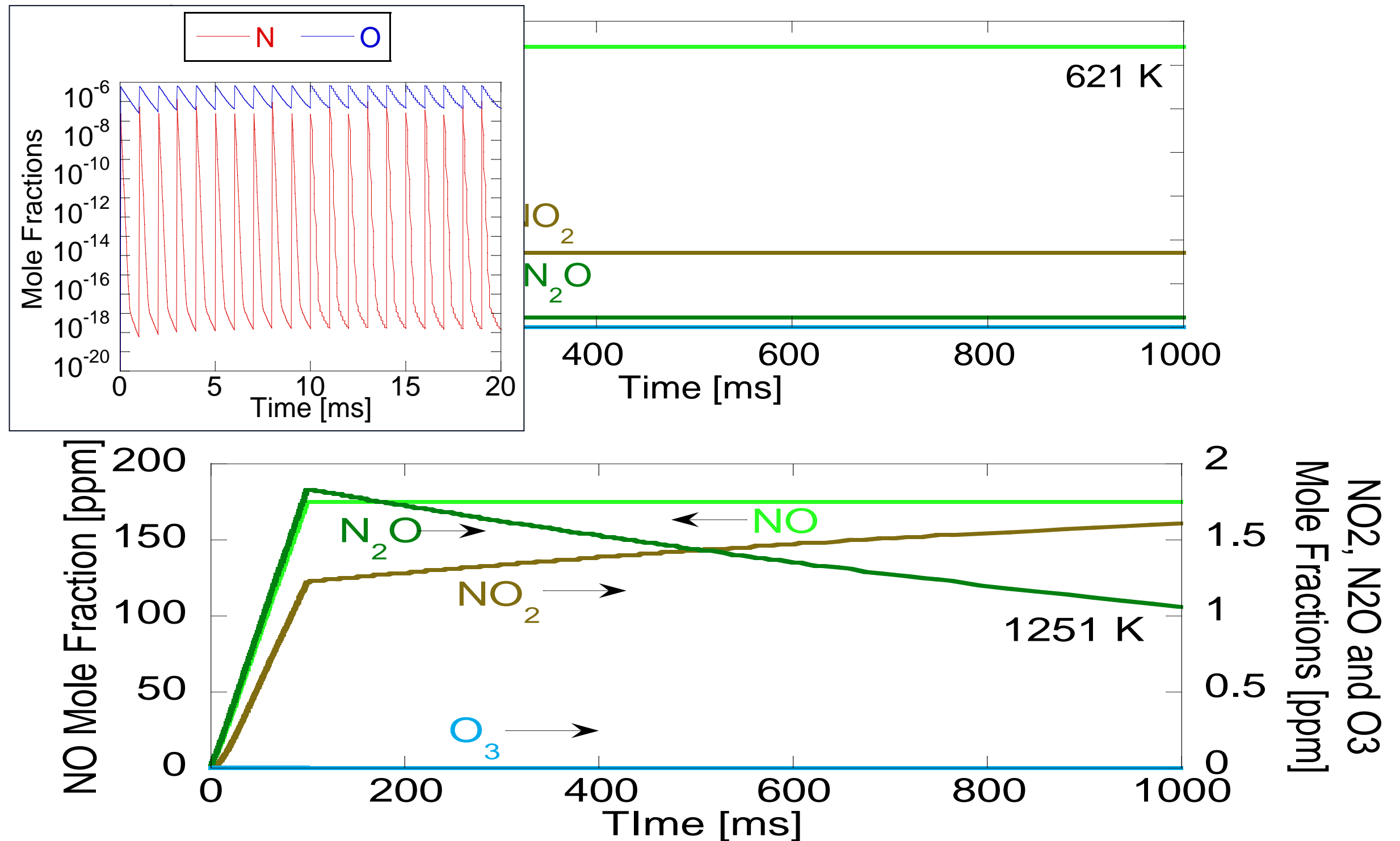
Discrete points: experimental results

Solid lines: numerical results



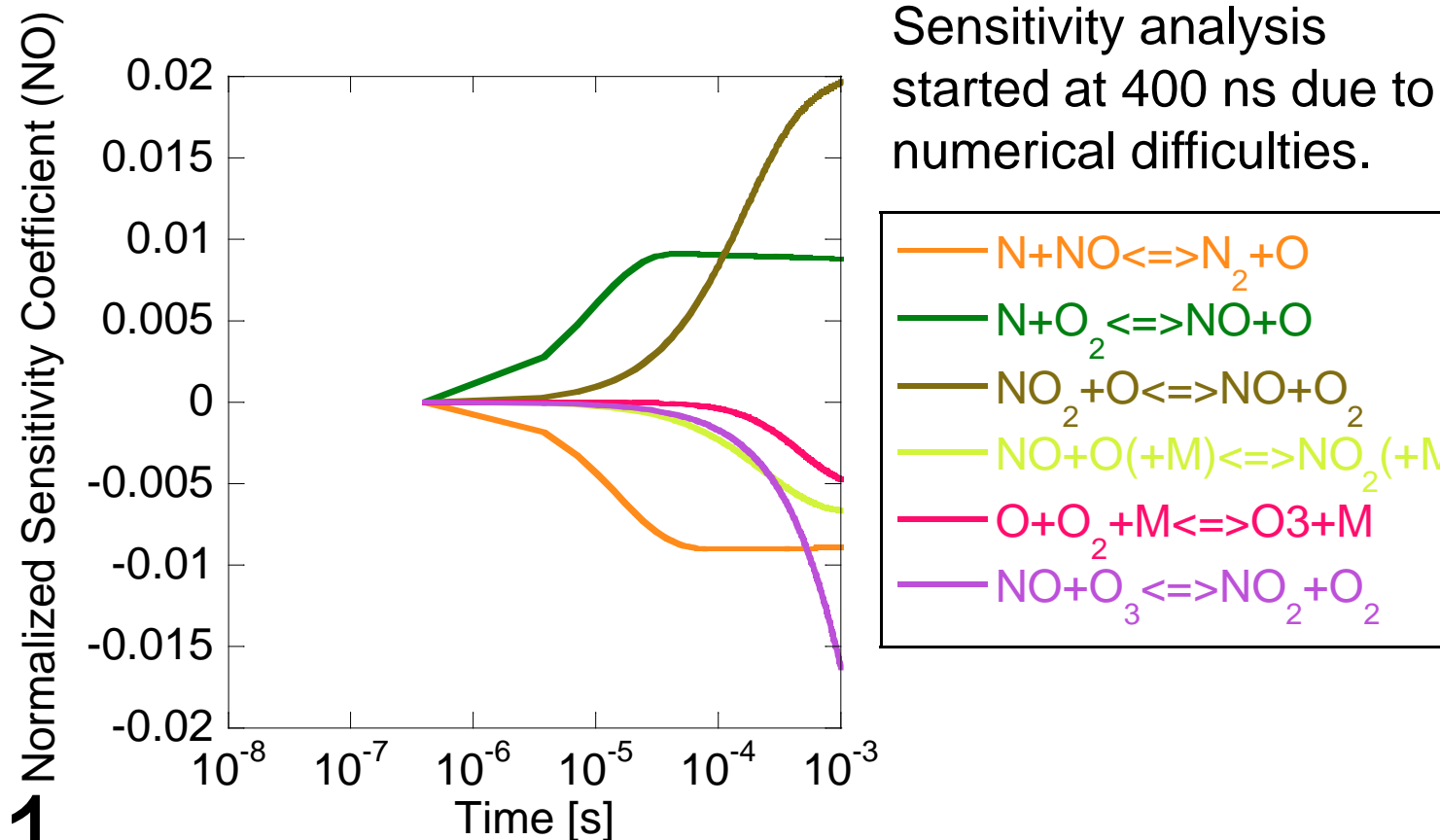
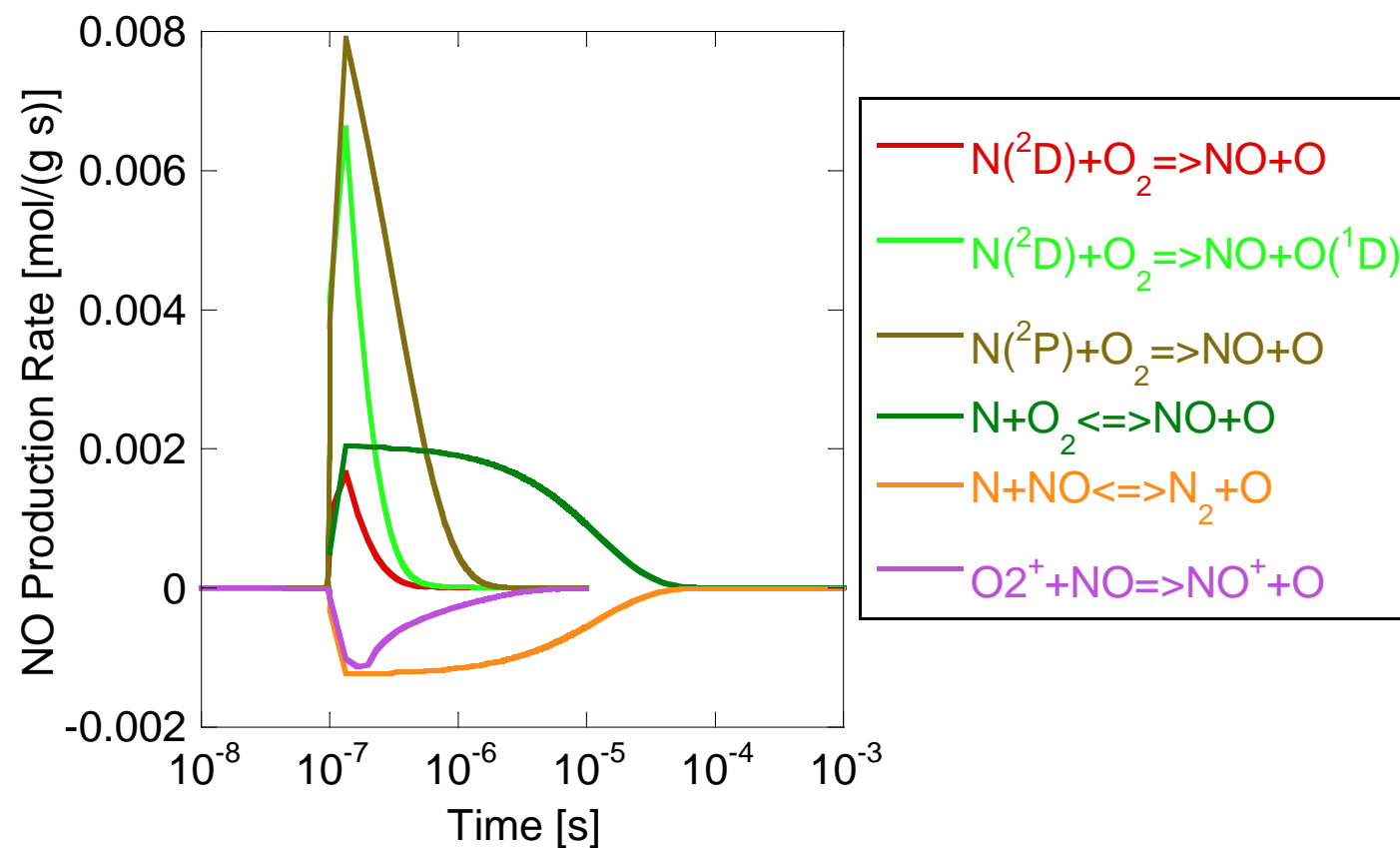
- N atom production results from electron impact dissociation of N₂.
- NO_x forms by $\text{N} + \text{O}_2 \rightarrow \text{NO} + \text{O}$. NO increases with temperature because of more N atom formation.
- Model overpredicts NO by a factor of 2. Most likely due to overprediction of N atom formation by electron impact dissociation. Total NO_x measured also decreases for temperatures above 1050 K.
- Higher portion of NO₂ at low temperatures due to the reaction $\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2$. O₃ decreases with temperature, so does NO₂.

Plasma Effects on NO_x Formation at Various Temperatures: Simulated Species History



NO Analyses (Production rate and Sensitivity)

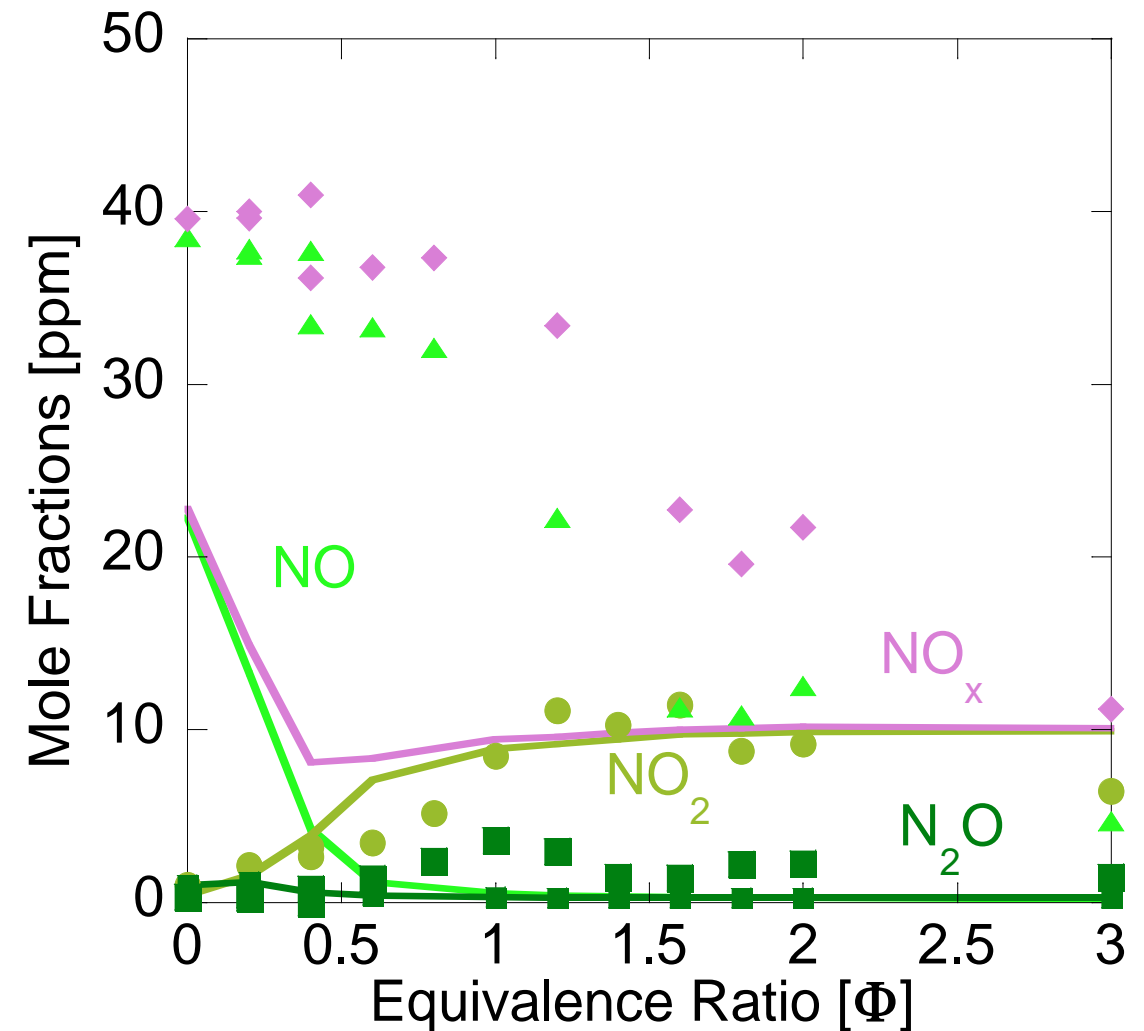
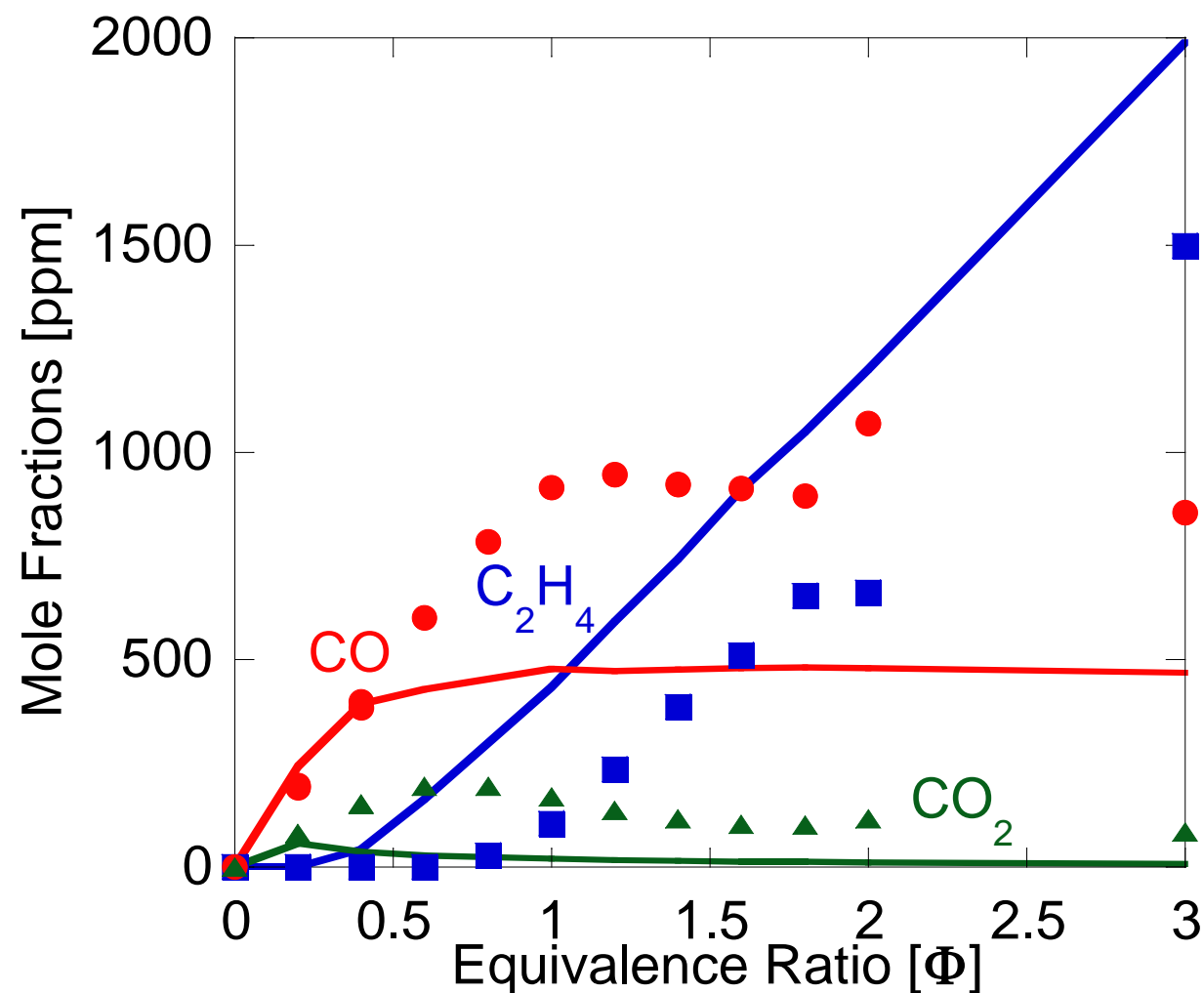
Pulse #100 of 620.7K case



- NO production due to $N+O_2=NO+O$. Reverse reaction $N+NO=N_2+O$ present because NO already built up.
- After 400 ns, NO is not sensitive to excited or ionized species any more.
- Sensitivity analysis shows three important mechanisms in the after glow: Zel'dovich thermal NO_x mechanism, $NO \leftrightarrow NO_2$ cycle by O atoms, and oxidation to NO_2 by O_3 .

Plasma Effects on NO_x Formation at Various Equivalence Ratios

9600 ppm N₂ / 2400 ppm O₂ / (800Φ) ppm C₂H₄ / Balance Ar
 1 atm, 814 K, τ_{plasma} = 70 ms, V_{peak} = 15 kV, f = 1 kHz



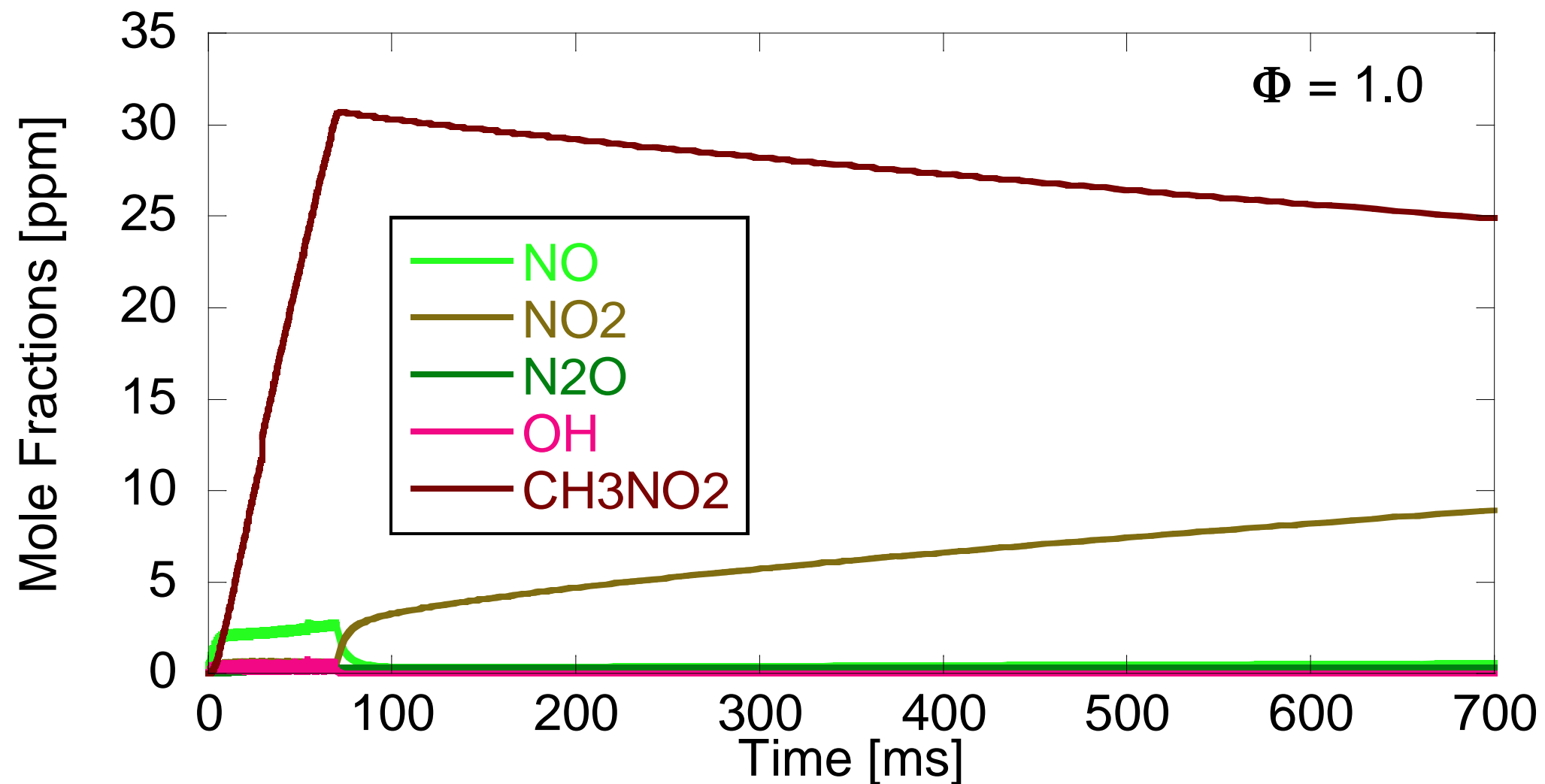
Experimental results

- For Φ > 0.5, NO_x formation decreases with Φ.
- Reaction rate constant of dissociative quenching of Ar* with fuel (Ar* + C₂H₄ → Ar + C₂H₃ + H or Ar* + C₂H₄ → Ar + C₂H₂ + H₂) is ≈ 10x faster than the one with N₂ (Ar* + N₂ → Ar + 2N).

Numerical results

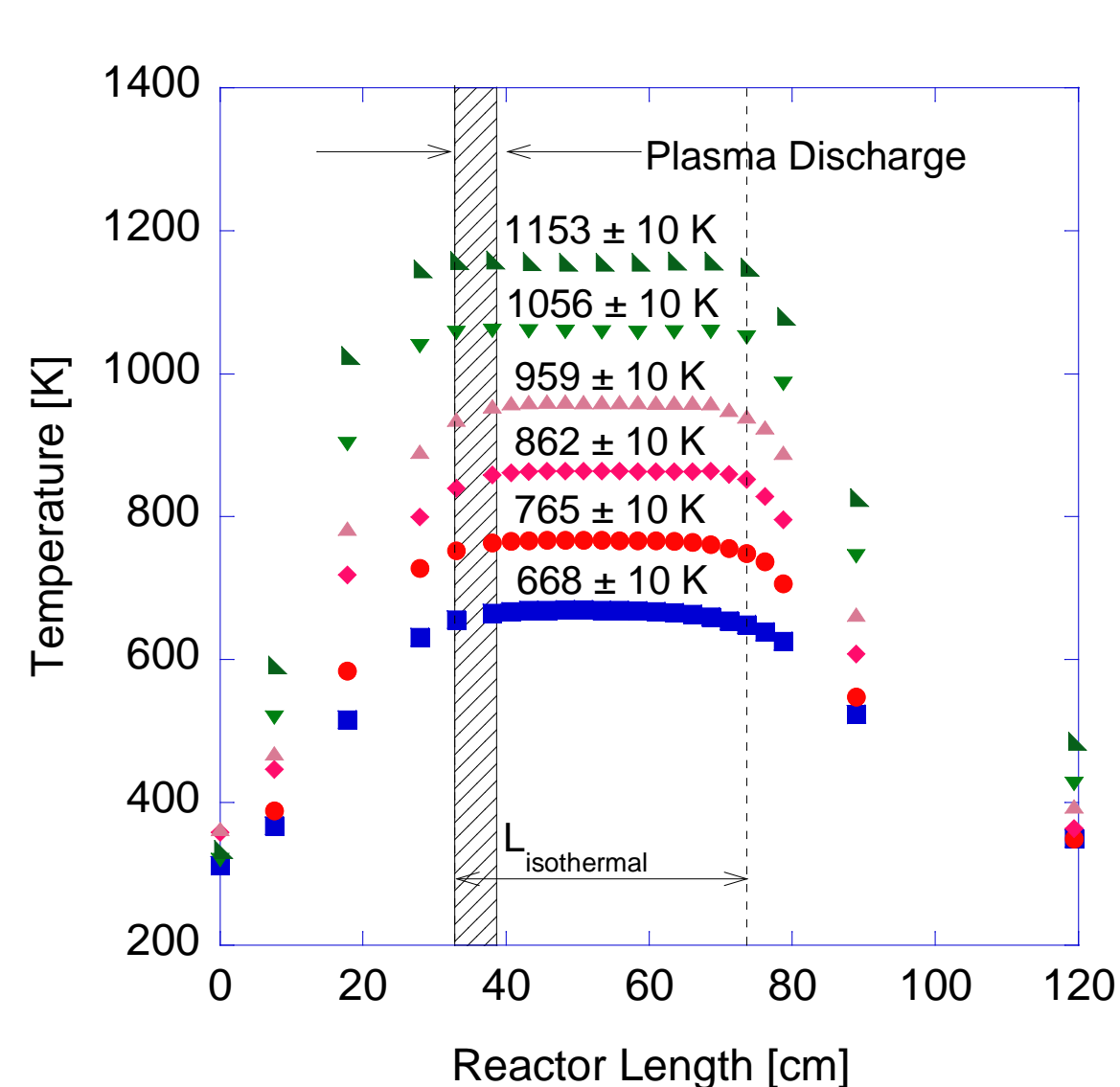
- Large discrepancies between experimental and numerical results. The trends of C-containing species profiles are qualitatively similar, but the matching of N-containing species are miserable.

What is happening in the code?

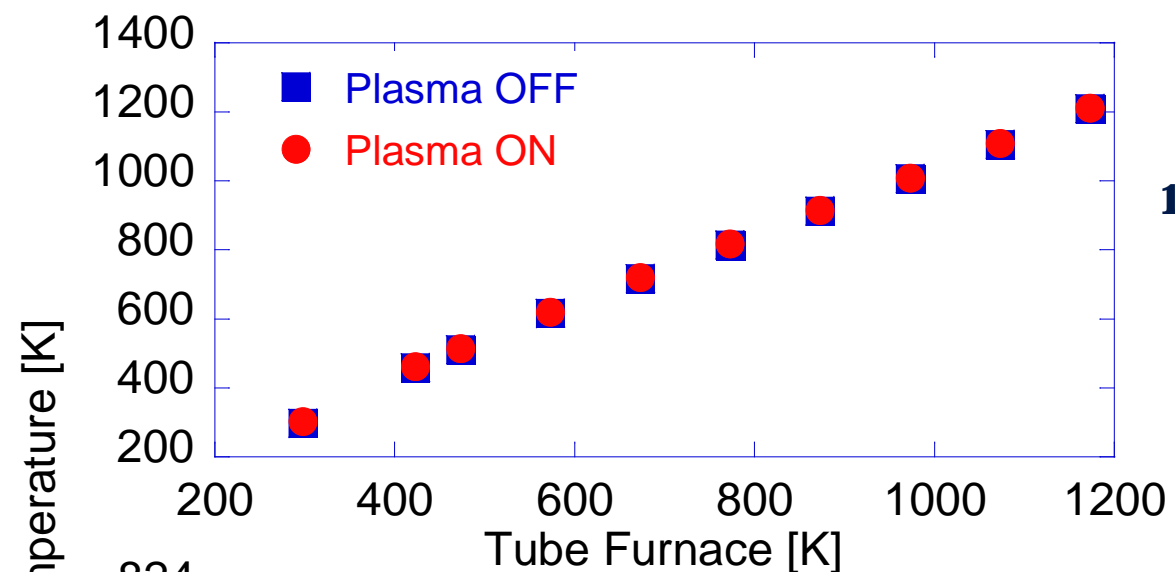


- NO forms in plasma region, and quickly converted to NO₂ by NO+HO₂ at the exit of plasma region.
- Large amount of nitromethane (CH₃NO₂) forms within the plasma region, by CH₃+NO₂(+M)=CH₃NO₂(+M). Downstream, CH₃NO₂ then decomposes.
- Current model missing many secondary reactions of CH₃NO₂ decomposition.

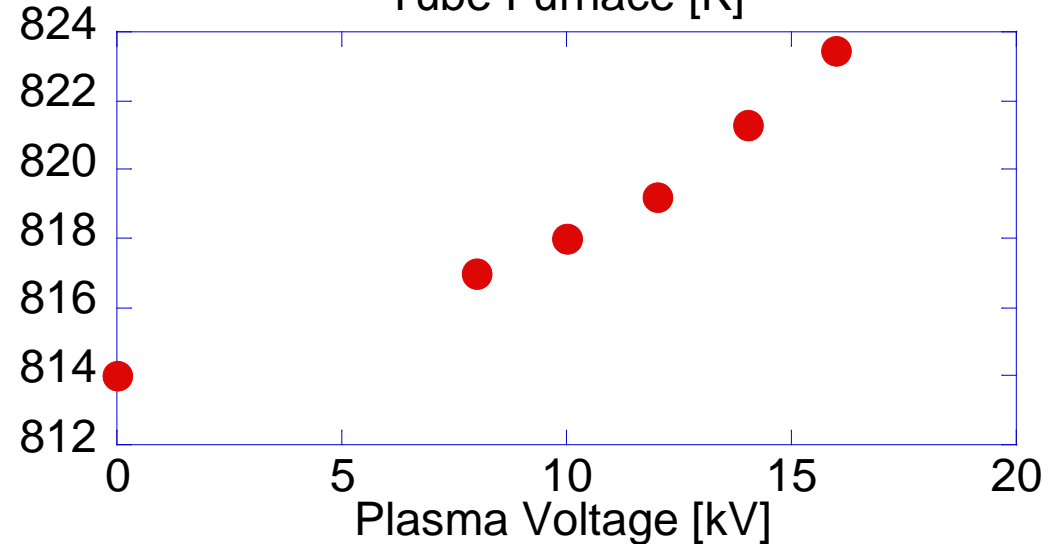
Operating Conditions - Temperature



**Reactor Temperature Profile
@ 1 LPM of Ar**



**1 LPM of Ar with
V = 10kV
 ν = 1 kHz**



**1 LPM of Ar
with 3 sccm O₂
 ν = 1 kHz**

Effect of Plasma Discharge on Temperature

- The measured temperature profiles are used to establish an empirical correlation with the tube furnace temperature over a range of $350 \text{ K} < T_{\text{iso}} < 1250 \text{ K}$. The correlation is used for kinetic modeling.
- Initial experiments verify that heating from the plasma discharge is negligible in the diluent flow
- In Ar/O₂ flow, $\sim 10 \text{ K}$ increase in gas temperature observed at the maximum voltage setting for a given reactor temperature of 814K



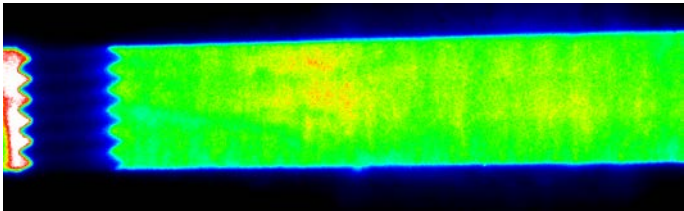
Operating Conditions - Plasma Discharge

Experimental Conditions: P = 1 atm, Q = 1 LPM Ar, Gate = 10 μ sec

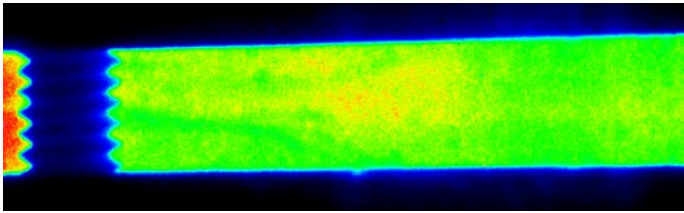
ICCD Multiple Images (average of 50)

298 K

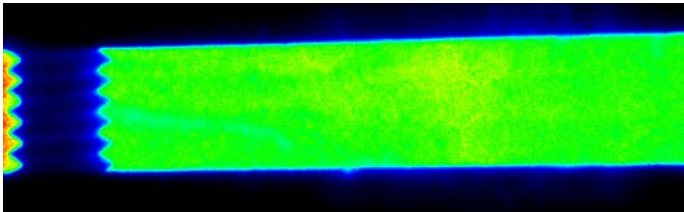
V = 15 kV
 ν = 1 kHz



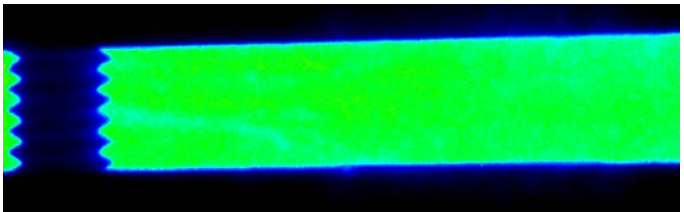
427 K



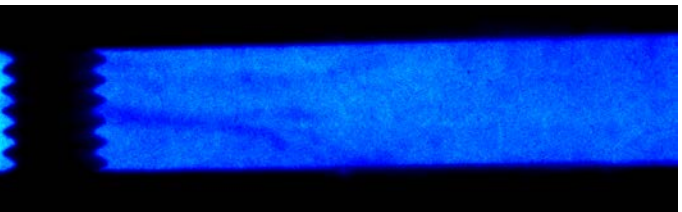
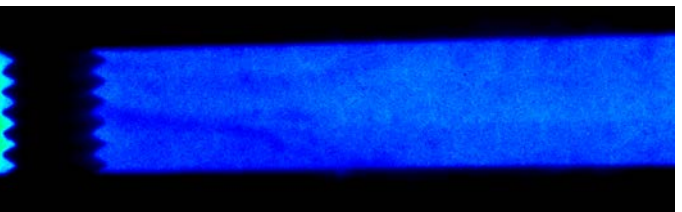
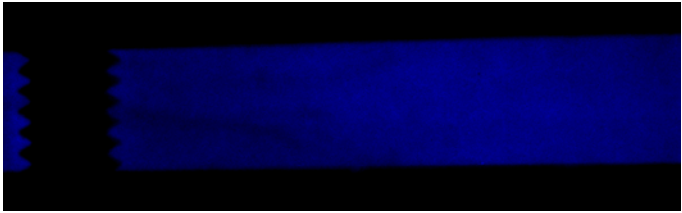
620 K



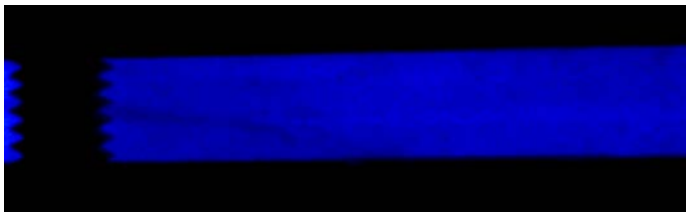
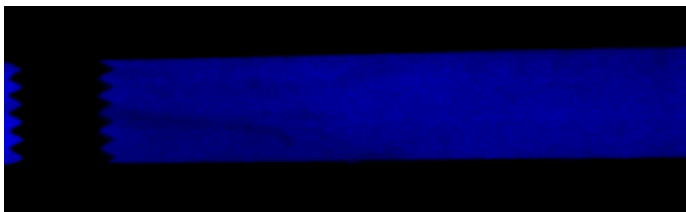
814 K



V = 10 kV
 ν = 1 kHz



V = 8 kV
 ν = 1 kHz



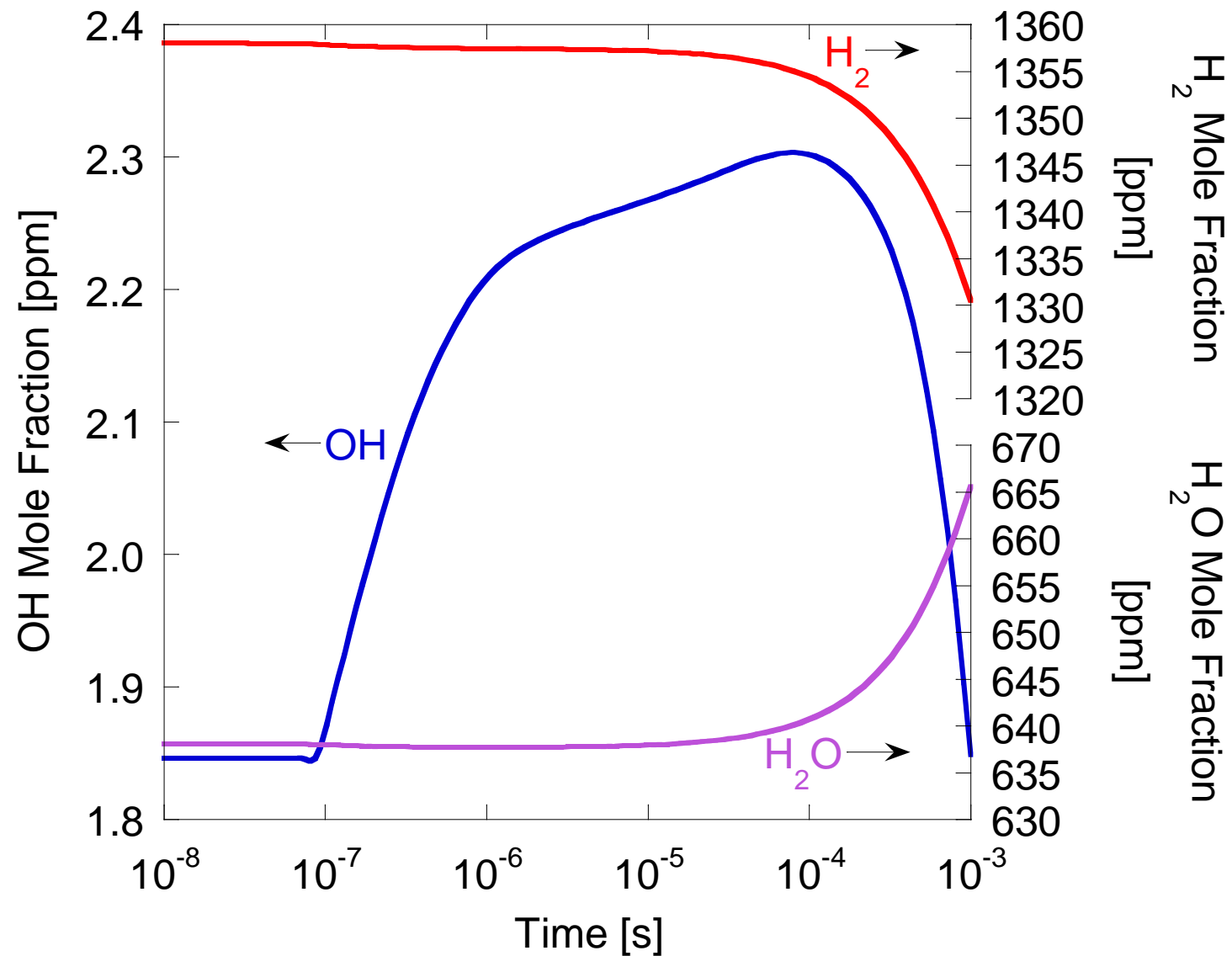
Details of Individual Pulse

Conditions: $P = 1$ atm, $T = 800$ K, $Q = 1$ LPM, 2000ppm H_2 /3000ppm O_2 / Ar by balance

Plasma Conditions: 10kV, $\nu = 1$ kHz

Pulse #22

Discharge at 77 ns, V_{peak} at 100 ns



Raw Data for Hydrocarbon Experiments

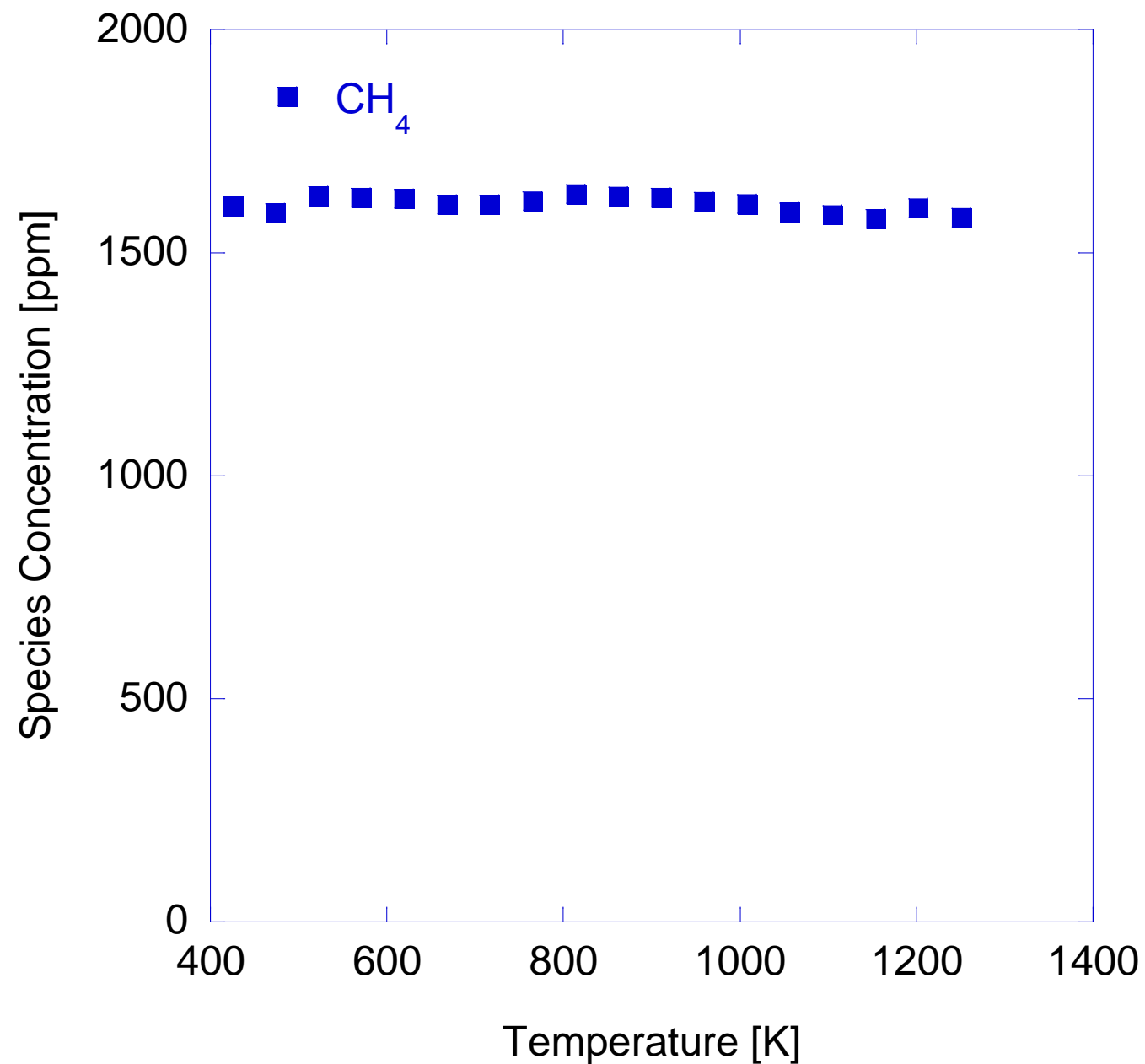


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CH₄ Thermal Oxidation

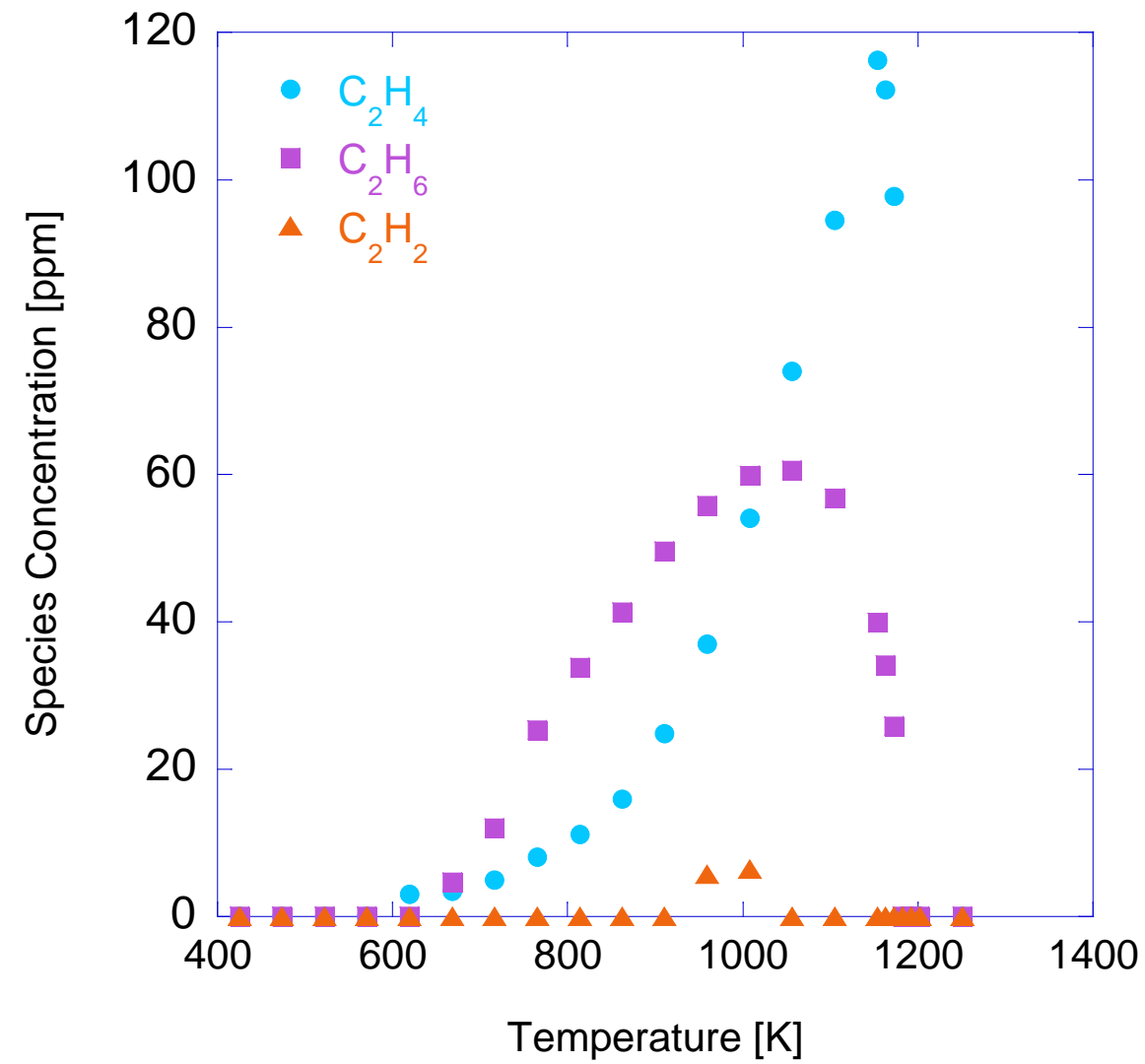
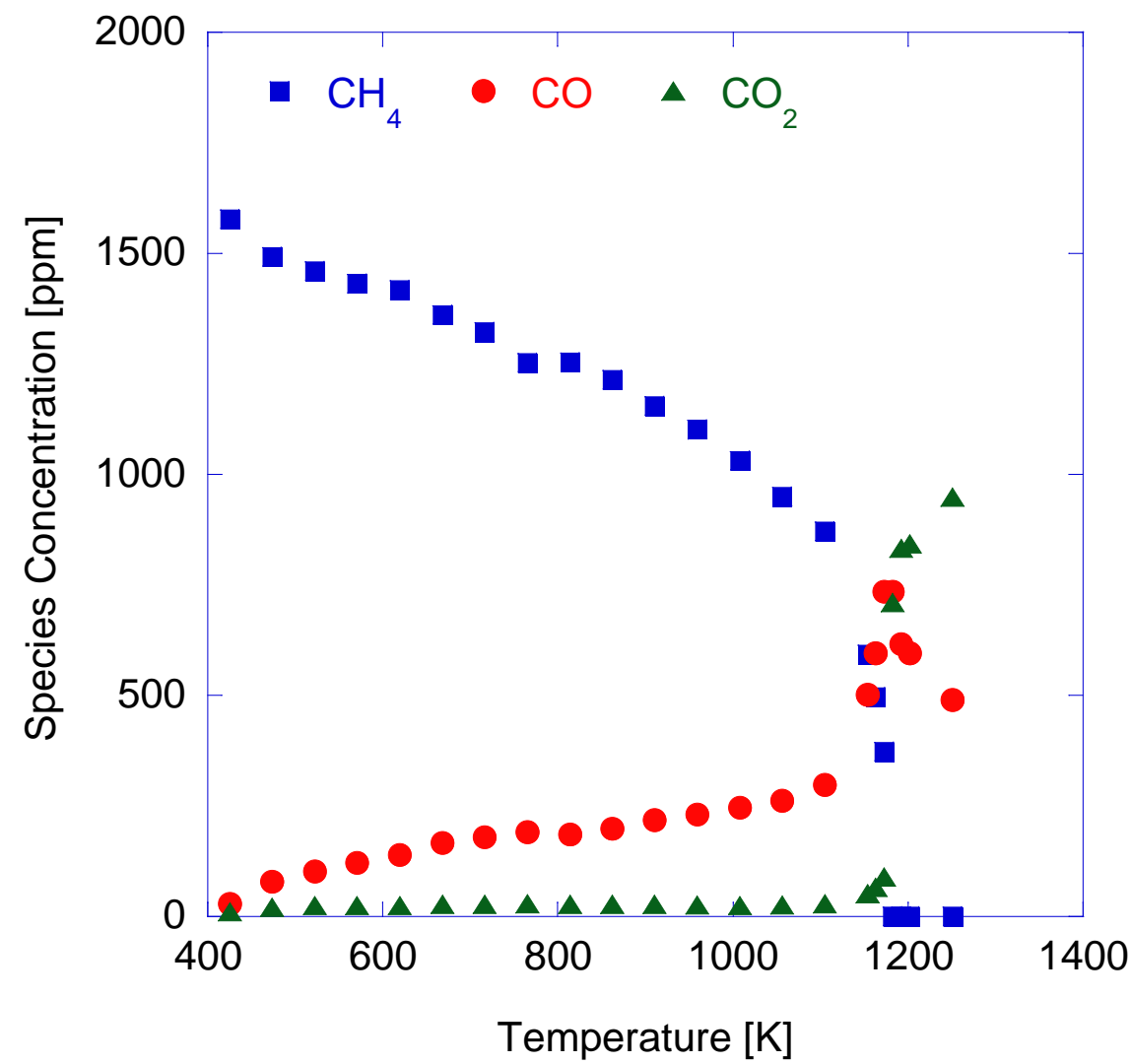
Experimental Conditions: P = 1 atm, Q = 1 LPM, 1600ppm CH₄/3000ppm O₂ / Ar by balance



CH₄ Plasma Oxidation

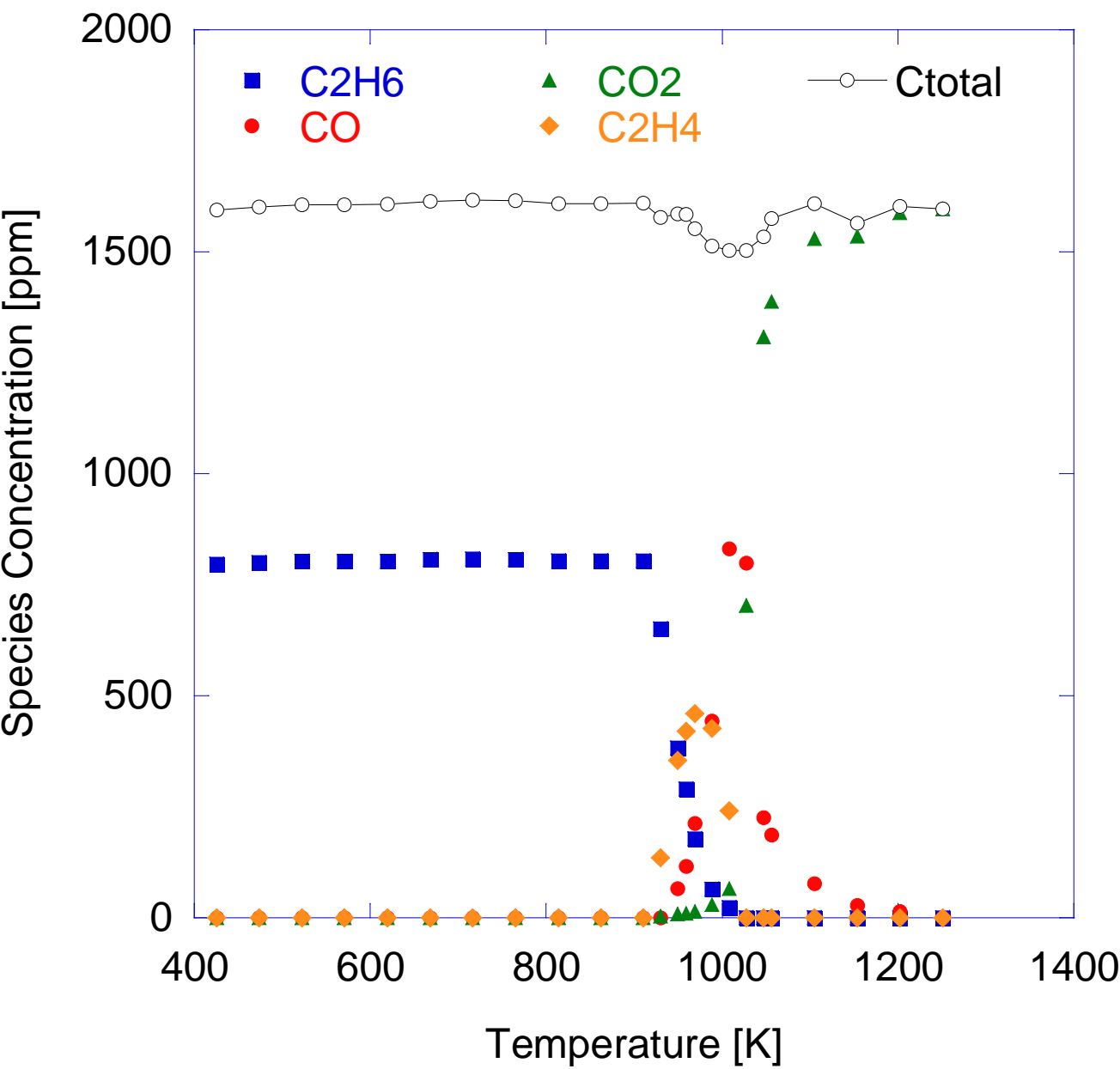
Experimental Conditions: P = 1 atm, Q = 1 LPM, 1600ppm CH₄/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz

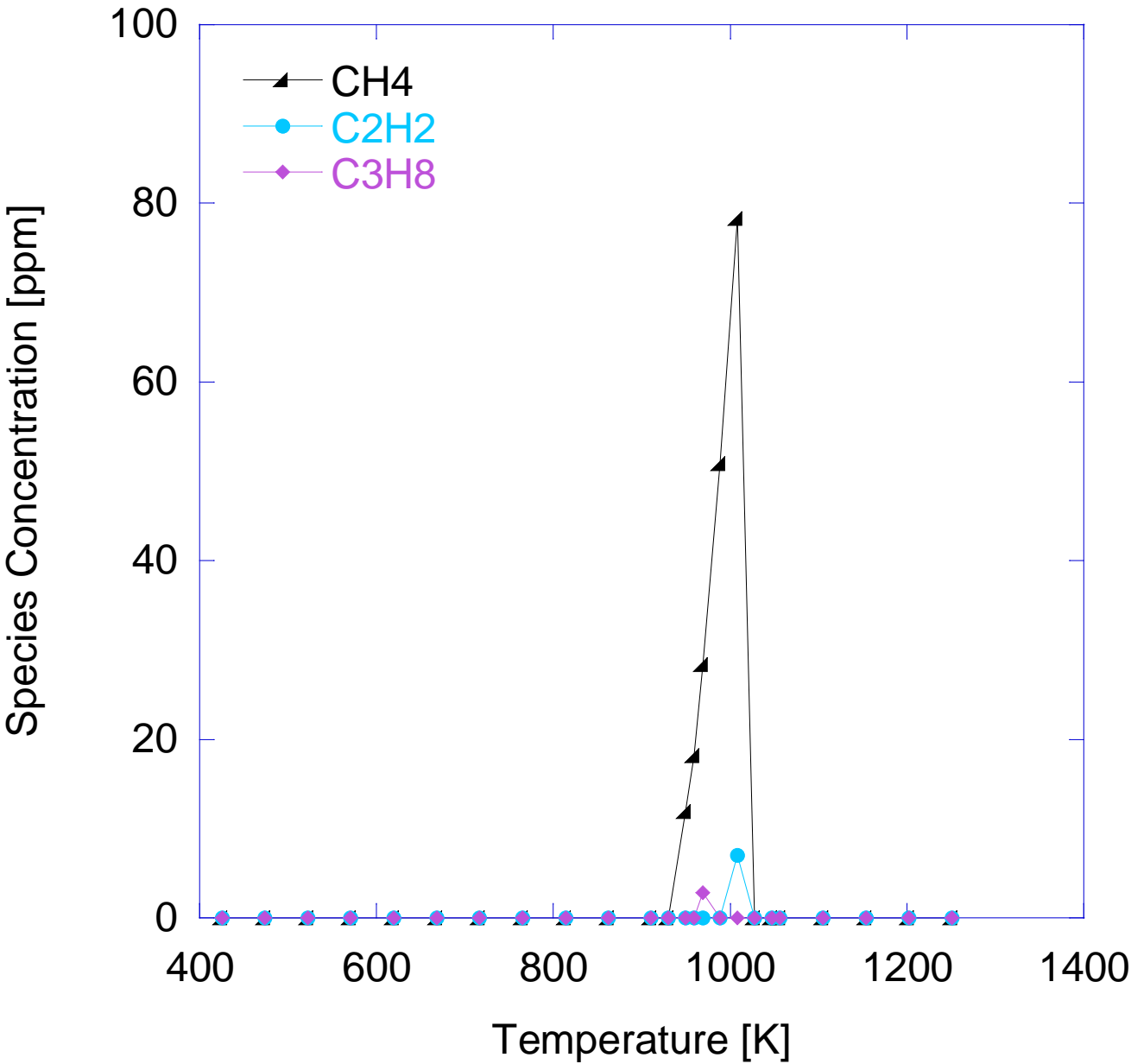


C₂H₆ Thermal Oxidation

Experimental Conditions: P = 1 atm, Q = 1 LPM, 800ppm C₂H₆/3000ppm O₂ / Ar by balance



Major Species

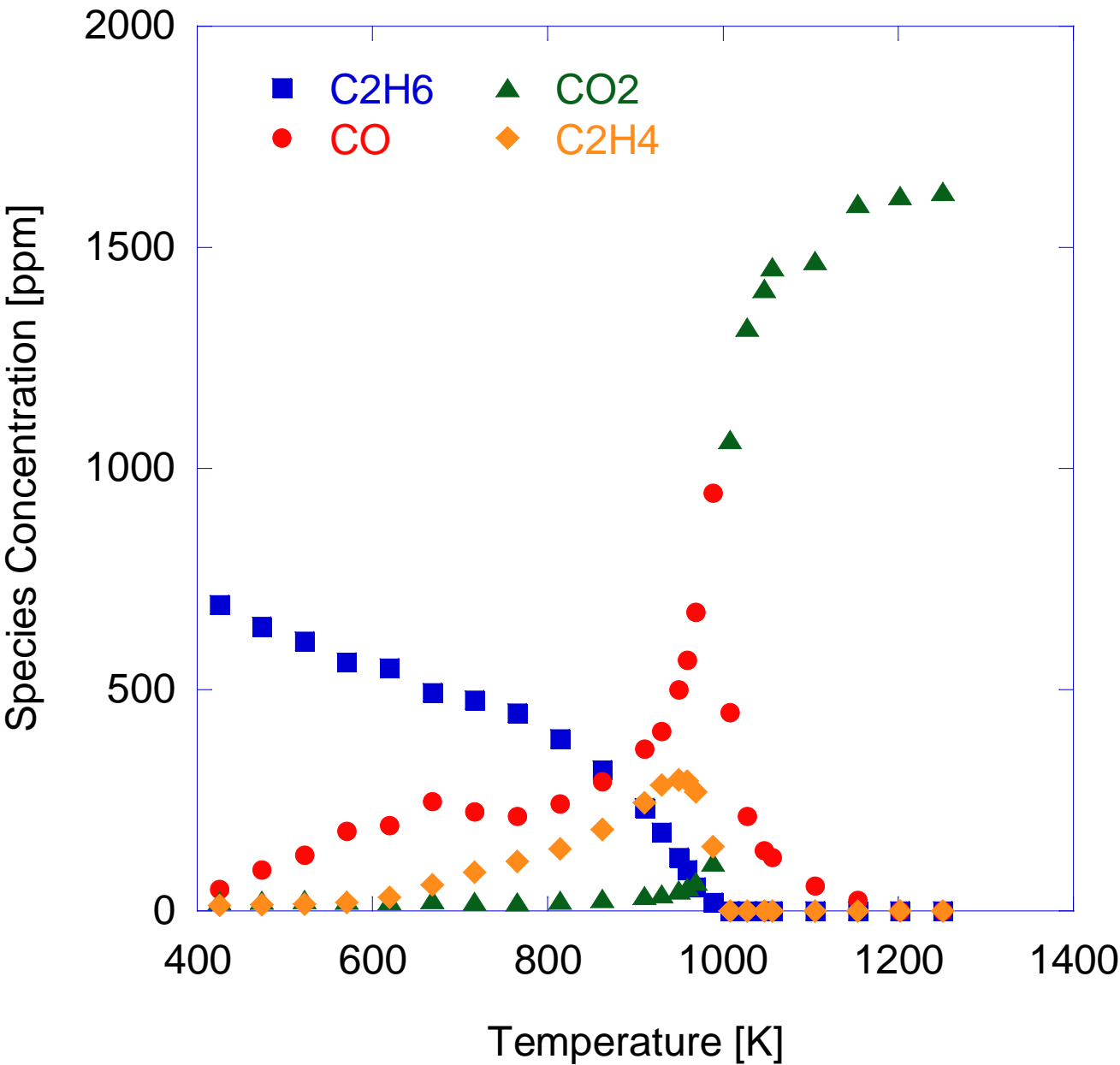


Minor Species

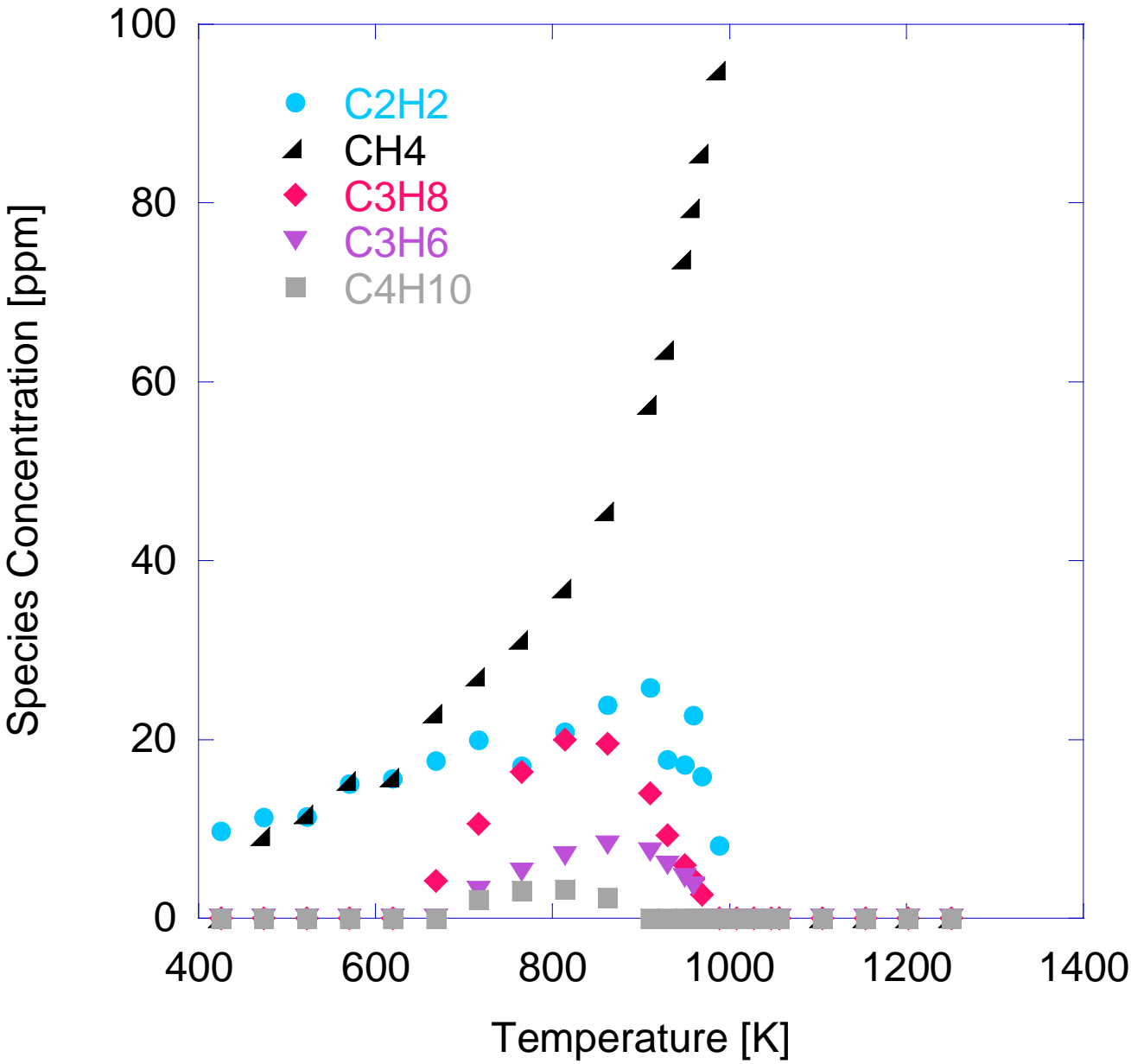
C₂H₆ Plasma Oxidation

Experimental Conditions: P = 1 atm, Q = 1 LPM, 800ppm C₂H₆/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz



Major Species

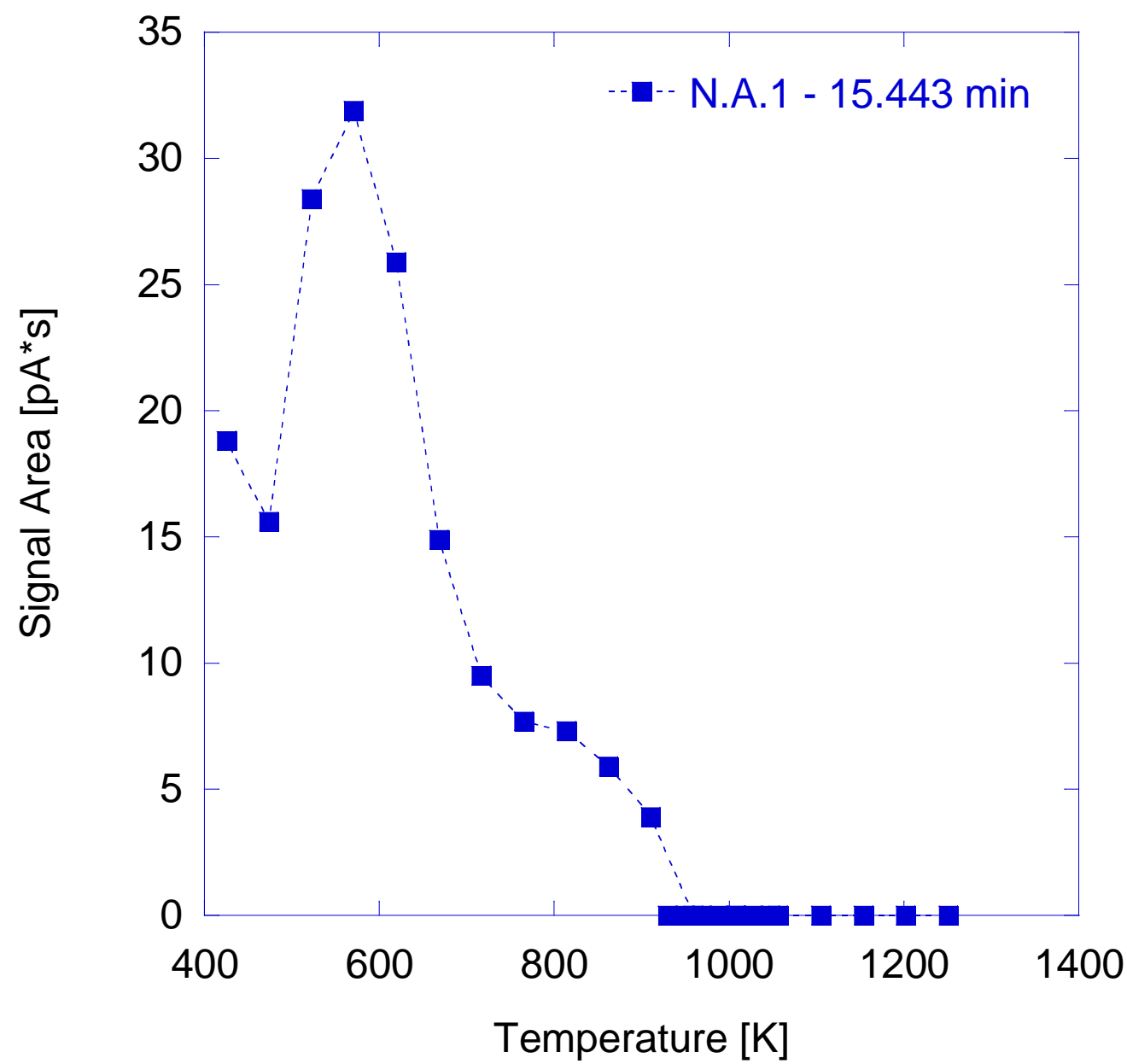


Minor Species

C₂H₆ Plasma Oxidation

Experimental Conditions: P = 1 atm, Q = 1 LPM, 800ppm C₂H₆/3000ppm O₂ / Ar by balance

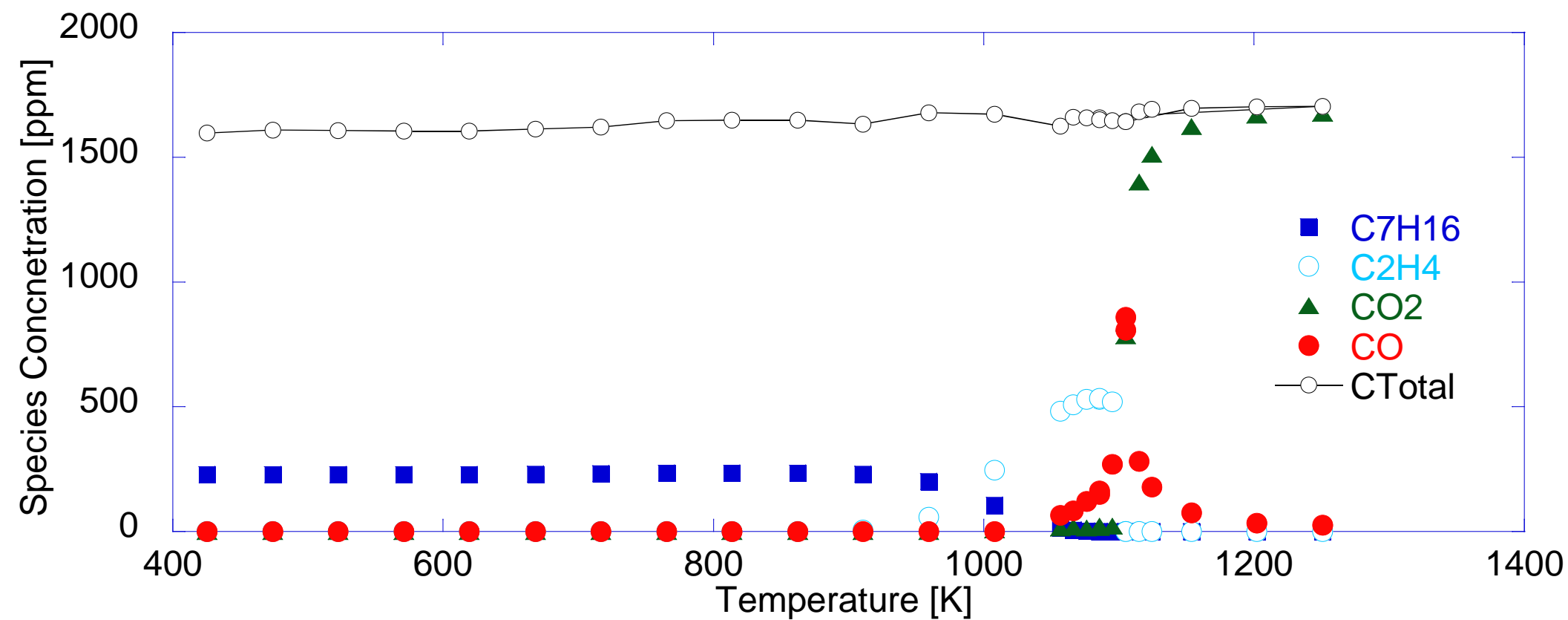
Plasma Conditions: 10 kV, ν = 1 kHz



Unknown Species

C₇H₁₆ Thermal Oxidation – Major Species

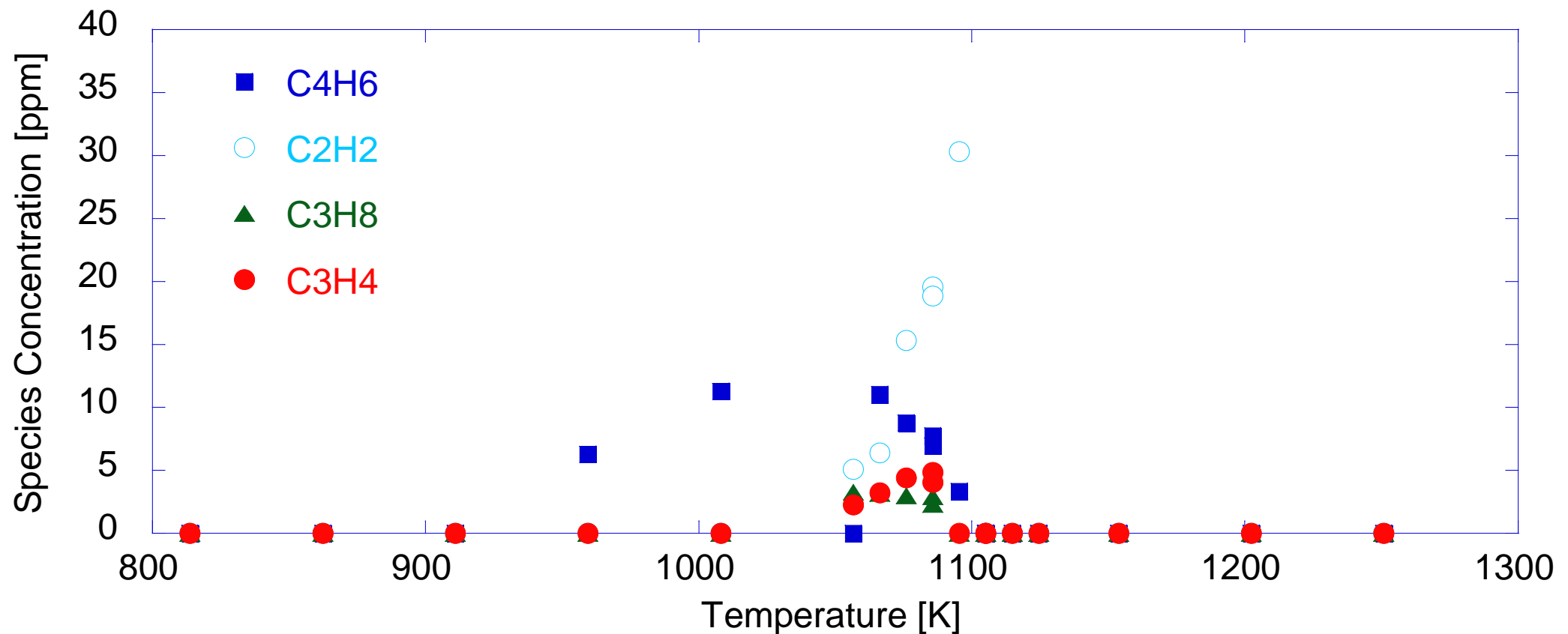
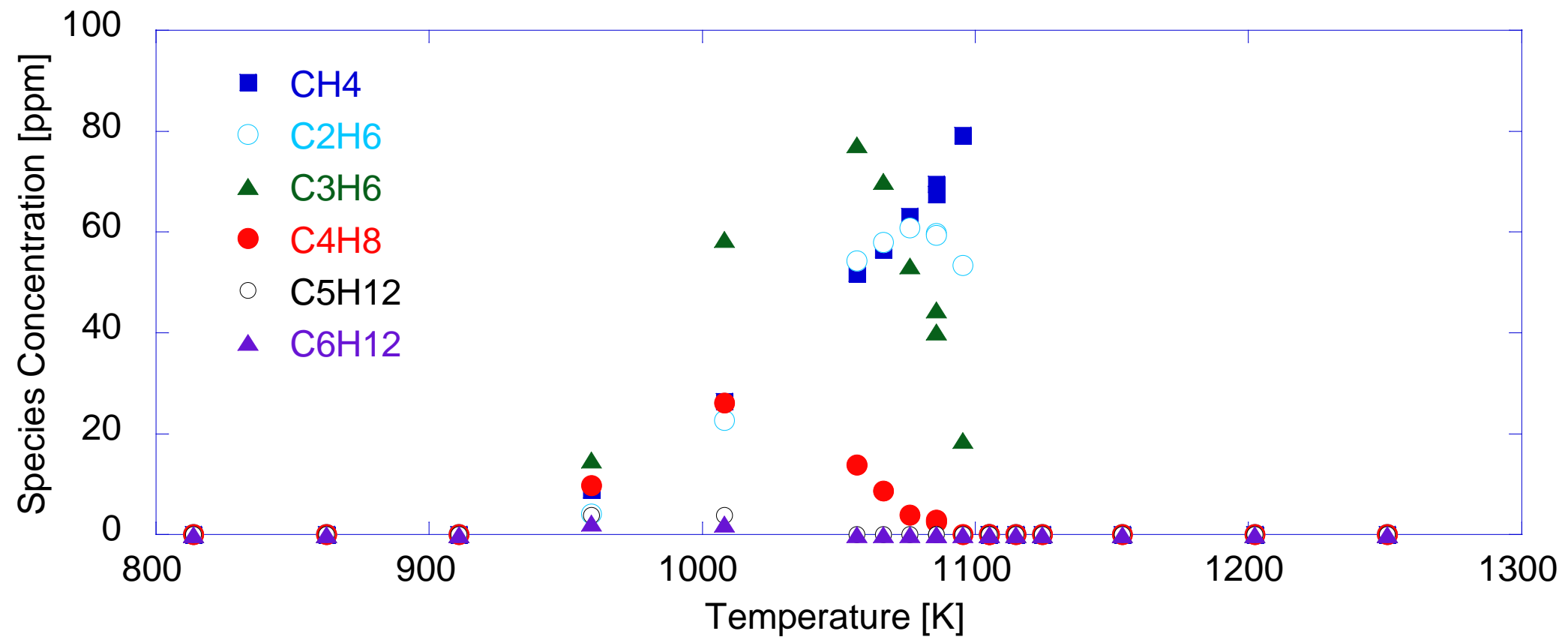
Experimental Conditions: P = 1 atm, Q = 1 LPM, 228ppm C₄H₁₀/3000ppm O₂ / Ar by balance



Major Species

C₇H₁₆ Thermal Oxidation – Minor Species

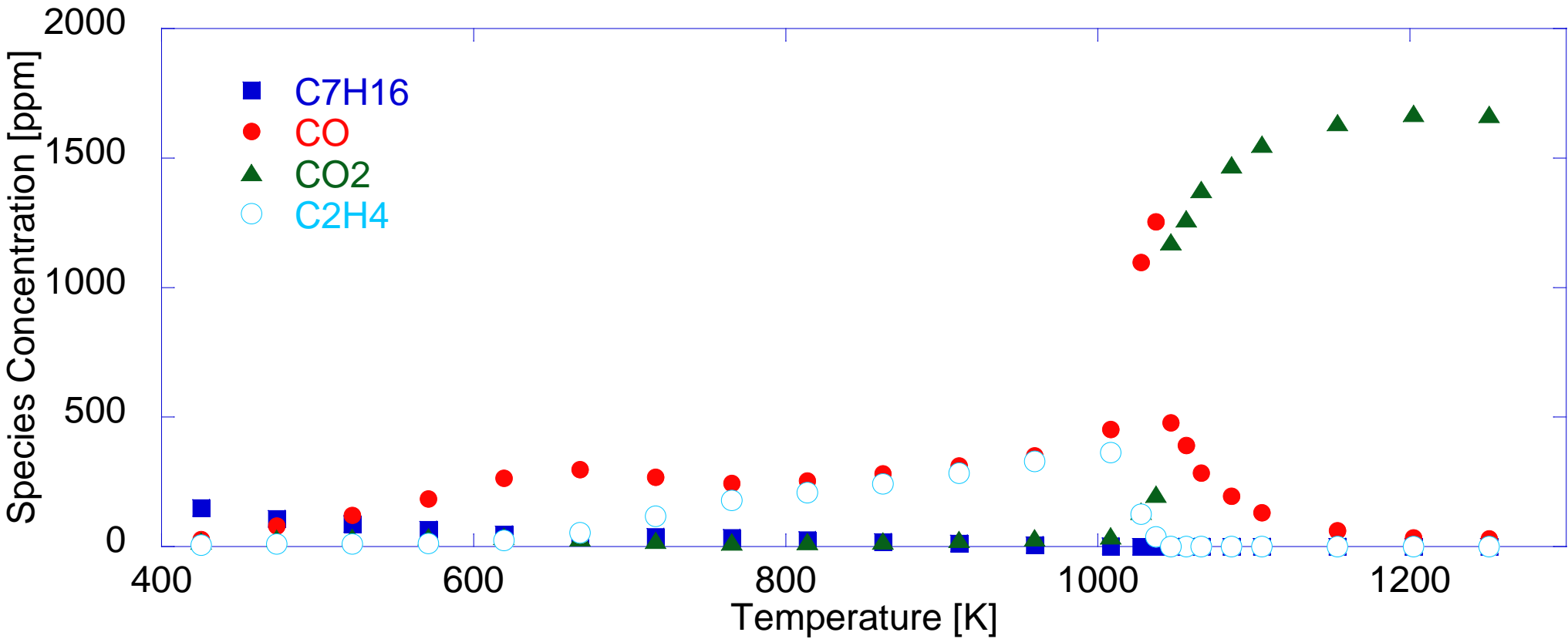
Experimental Conditions: P = 1 atm, Q = 1 LPM, 228ppm C₄H₁₀/3000ppm O₂ / Ar by balance



C₇H₁₆ Plasma Oxidation – Major Species

Experimental Conditions: P = 1 atm, Q = 1 LPM, 228ppm C₄H₁₀/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz

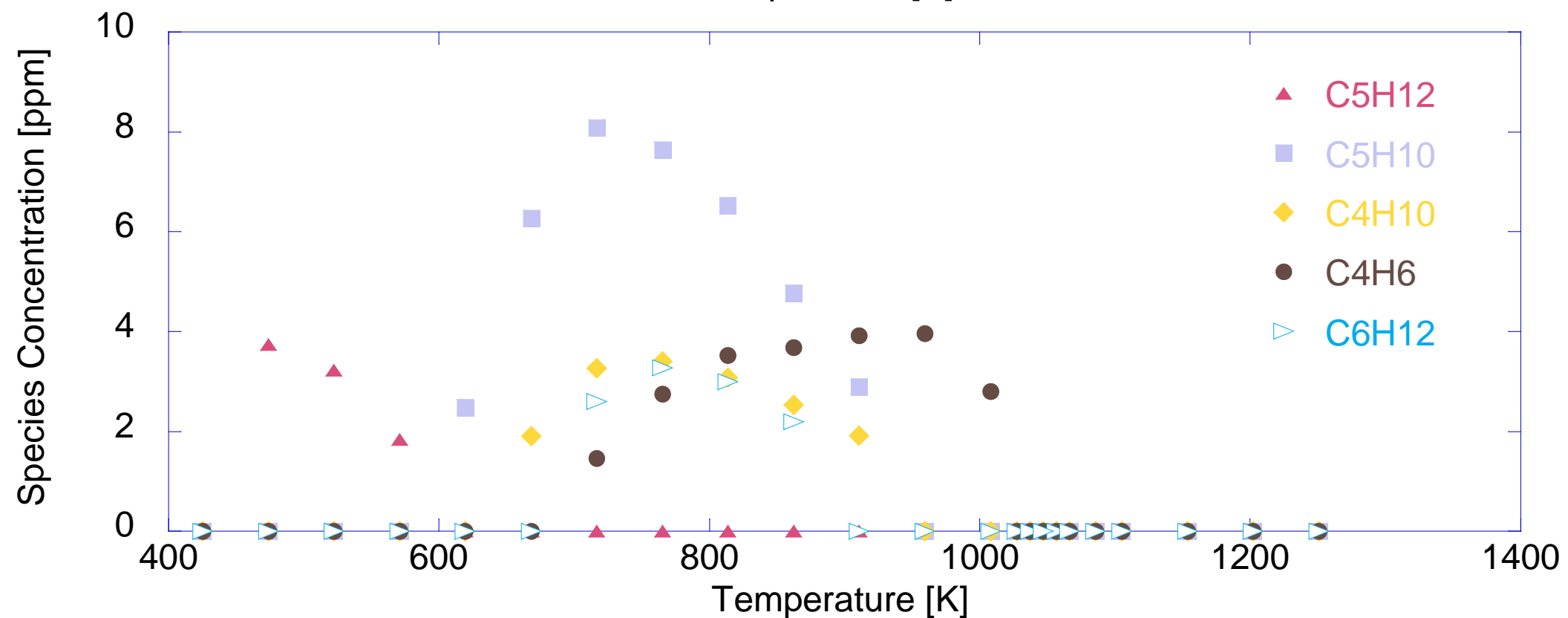
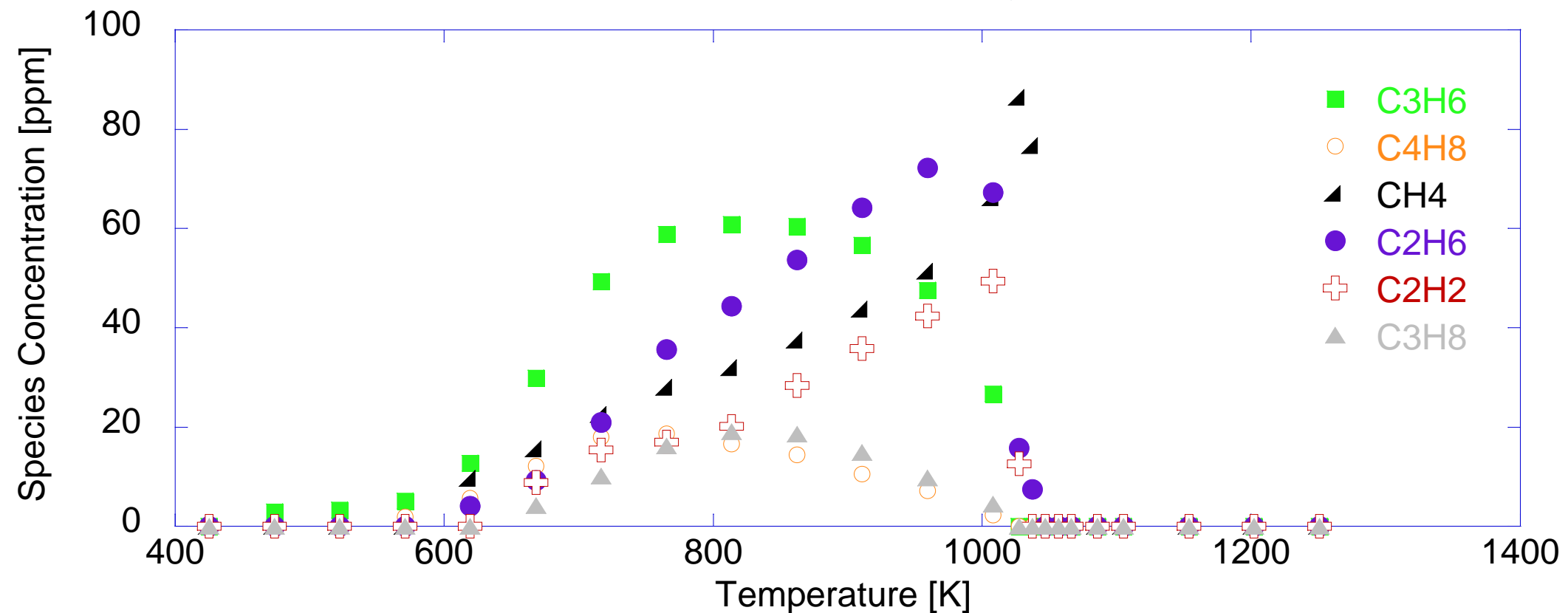


Major Species

C₇H₁₆ Plasma Oxidation – Minor Species

Experimental Conditions: P = 1 atm, Q = 1 LPM, 228ppm C₄H₁₀/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz



C₇H₁₆ Plasma Oxidation – Unknowns

Experimental Conditions: P = 1 atm, Q = 1 LPM, 228ppm C₄H₁₀/3000ppm O₂ / Ar by balance

Plasma Conditions: 10 kV, ν = 1 kHz

